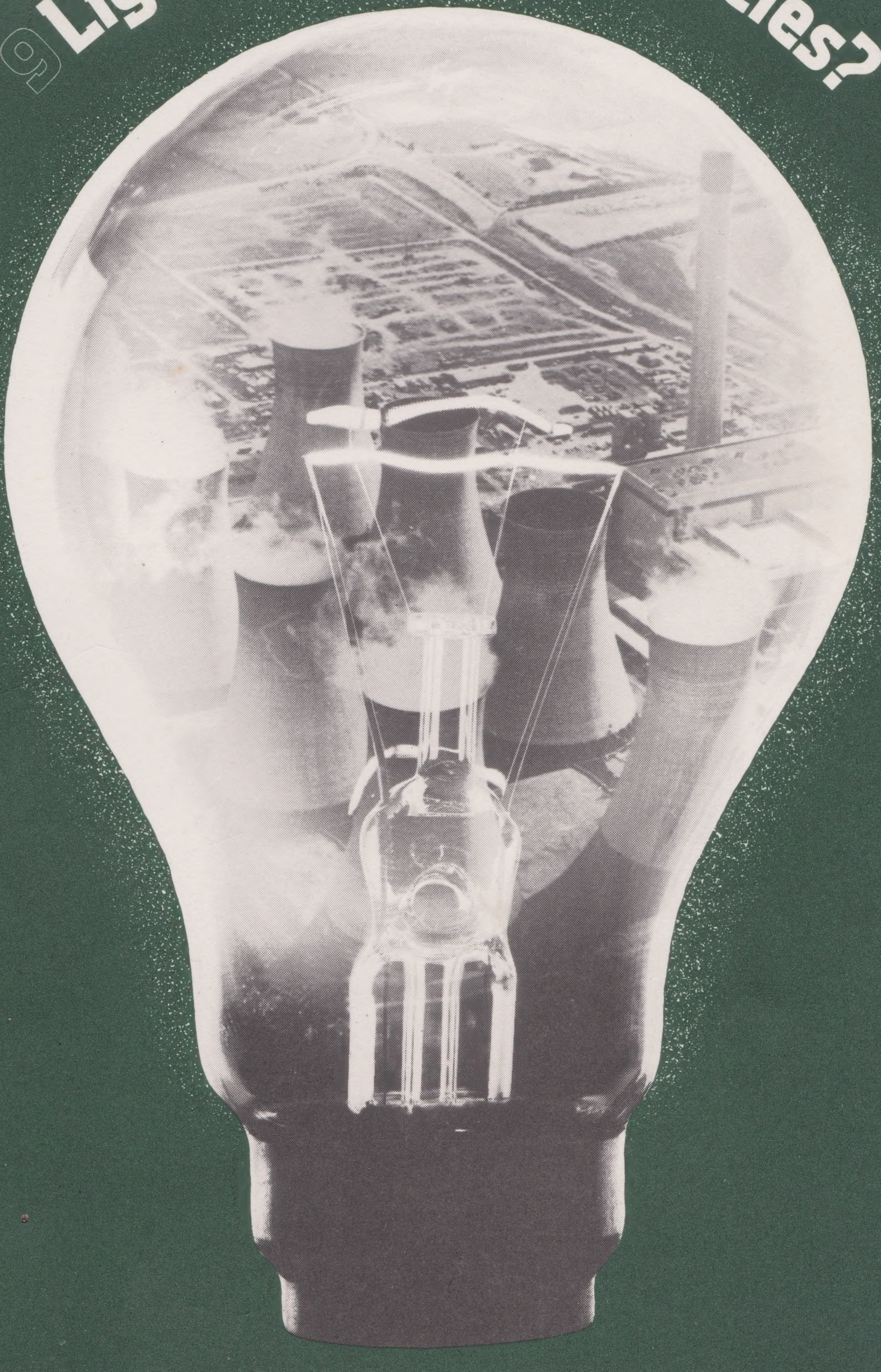
S101 Units 8 and 9

THE OPEN UNIVERSITY

Science : A Foundation Course

8 Energy

9 Light: Waves or Particles?



The Open University

Science: A Foundation Course

Unit 8
Energy

Prepared by the Science Foundation Course Team

The Open University Press

SCIENCE

S101 Course Team List

A note about the authorship of this text

This text is one of a series that constitutes a component part of the Science Foundation Course. The other components are a series of television and radio programmes, audio-vision materials, home experiments, assignments and a summer school.

The Course has been produced by a team, which accepts responsibility for it.

The Science Foundation Course Team

Mike Pentz (*Chairman and General Editor*)

Francis Aprahamian (*Course Editor*)
David Broadhurst (*Physics*)
Geoff Brown (*Earth Sciences*)
Neil Chalmers (*Biology*)
Glen Davey (*Course Coordinator*)
Graham Farmelo (*Physics*)
Peter Francis (*Earth Sciences*)
Stuart Freake (*Physics*)
Anna Furth (*Biology*)
Denis Gartside (*BBC*)
Charles Harding (*Chemistry*)
Keith Hodgkinson (*Physics*)
Stephen Hurry (*Biology*)
David Jackson (*BBC*)
David Johnson (*Chemistry*)
Tony Jolly (*BBC*)
Roger Jones (*BBC*)
Patricia McCurry (*BBC*)
Perry Morley (*Editor*)
Jane Nelson (*Chemistry*)
Ian Nuttall (*Editor*)
Irene Ridge (*Biology*)
David Roberts (*Chemistry*)
Shelagh Ross (*Course Coordinator*)
Eileen Scanlon (*Research Fellow, Evaluation*)
Milo Shott (*Physics*)
Jacqueline Stewart (*Editor*)
John Stratford (*BBC*)
Steve Swithenby (*Physics*)
Peggy Varley (*Biology*)
Kiki Warr (*Chemistry*)
Barrie Whatley (*BBC*)
Dave Williams (*Earth Sciences*)
Chris Wilson (*Earth Sciences*)

The following people assisted with particular parts or aspects of the Course:

Tel Bailey (*Tutor*)
Mary Bell (*Biology*)
Frances Berrigan (*IET*)
James Brennan (*Biology, Bridgewater State College, USA*)
Joan Brown (*Earth Sciences*)
Bob Cordell (*Biology*)
Beryl Crooks (*IET*)
Linda Fawke (*Tutor*)
Michael Gagan (*Chemistry*)
Ian Gass (*Earth Sciences*)
Ros Hamilton (*Tutor*)
Robin Harding (*Biology*)
Barbara Hodgson (*IET*)
Jen Horgan (*Tutor*)
Graham Jenkins (*Earth Sciences*)
Barrie Jones (*Physics*)
Paul Lyle (*Tutor*)
John Marshall (*Senior Counsellor*)
Bob Maybury (*Chemistry, UNESCO*)
Bob McConnell (*Earth Sciences, Virginia Polytechnic and the State University, USA*)
Laurie Melton (*Librarian*)
Reg Melton (*IET*)
Yow Lam Oh (*Home Experiments, Caulfield Institute of Technology, Australia*)
Robin Russell (*Chemistry*)
Meg Sheffield (*BBC*)
Jane Sheppard (*Designer*)
Jennie Simmons (*Home Experiment Kit Coordinator*)
Peter Smith (*Earth Sciences*)
Russell Stannard (*Physics*)
Charles Turner (*Earth Sciences*)
Arthur Vialls (*BBC*)
John Walters (*Physics*)
Pete Wood (*Home Experiment Kit Coordinator*)
John Wright (*Earth Sciences*)
Martin Wright (*BBC*)

The Open University Press,
Walton Hall, Milton Keynes.

First published 1979. Reprinted with corrections 1982.

Designed by the Media Development Group of the Open University.

Printed in Great Britain by Eyre & Spottiswoode Ltd., at Grosvenor Press, Portsmouth.

ISBN 0 335 08058 8

This text forms part of an Open University Course. The complete list of Units in the Course appears at the end of this text.

For general availability of supporting material referred to in this text please write to Open University Educational Enterprises Ltd., 12 Cofferidge Close, Stony Stratford, Milton Keynes, MK11 1BY, Great Britain.

Further information on Open University Courses may be obtained from the Admissions Office, The Open University, P.O. Box 48, Walton Hall, Milton Keynes, MK7 6AB.

1.2

Contents

	Table A List of terms and concepts in Unit 8	4
	Study guide	5
1	**Introduction**	7
2	**Different forms of energy**	7
3	**Conservation of energy**	12
3.1	Introduction	12
3.2	Energy is always conserved	12
4	**Measuring energy**	13
4.1	Introduction	13
4.2	The energy required to move objects	14
4.3	Units of energy	15
4.4	Power	18
5	**The energy transferred by unevenly applied forces**	18
6	**Kinetic energy**	23
6.1	Introduction	23
6.2	On what does the kinetic energy of an object depend?	23
6.3	How to work out the kinetic energy of a moving object	23
6.4	An experiment to verify the principle of conservation of energy	24
6.5	An aside—the principle of conservation of momentum	27
7	**Gravitational energy**	28
7.1	Introduction	28
7.2	How to calculate the gravitational energy of an object	28
7.3	Conversion of gravitational energy into kinetic energy—the bouncing ball	29
7.4	Energy graphs	31
7.5	The story so far	32
7.6	More about the bouncing ball	33
8	**Heat energy**	34
8.1	Introduction	34
8.2	Joule's apparatus	34
8.3	The difference between heat energy and temperature	35
8.4	More about Joule's experiment	37
9	**A closer look at heat energy and temperature**	39
9.1	Heat energy, temperature and atoms	39
9.2	Solids, liquids and gases	40
10	**Electrical energy**	42
10.1	Introduction	42
10.2	Forces between charges	42
10.3	The flow of charge—electric current	44
11	**An energy crisis?**	46
	Appendix 1	48
	Aims and Objectives	49
	ITQ answers and comments	50
	SAQ answers and comments	51

Table A List of terms and concepts in Unit 8

Assumed from general knowledge	Introduced in a previous Unit	Unit No.	Introduced in this Unit	Page No.
billiards	acceleration	3	amp A	45
energy crisis	acceleration due to gravity g	3	boiling temperature	35
fluorescent light	asthenosphere	4	chemical energy	8
friction	average speed	3	coulomb C	43
fuels—coal, gas and oil	battery	5	Coulomb's law	43
mains supply of electricity	charge	5	diffusion	39
microscope	electric current I	5	elastic collision	24
random motion	electron	5	electrical energy E_{el}	44
thermal insulation	energy	4	electromagnetic force	44
thermometer	force	3	electronvolt eV	17
tungsten-filament bulb	lithosphere	4	electrostatic force F_{el}	42
	magnetic force	5	energy conversion	8
	momentum p	3	energy graphs	31
	newton N	3	energy of actual motion	8
	Newton's second law	3	energy of potential motion	8
	plate tectonic process	6/7	energy transfer	8
	principle of conservation of momentum	TV03	fuel crisis	47
			gravitational energy E_g	28
	speed	3	heat energy E_h	37
	stroboscope	3	joule J	15
	velocity	3	Joule's apparatus	34
			kinetic energy E_k	24
			light energy	10
			magnetic energy	8
			Maxwell–Boltzmann distribution	39
			matter energy	10
			melting temperature	41
			muscular energy	8
			physical system	7
			positive and negative charge	42
			power	18
			principle of conservation of energy	12
			sound energy	10
			specific heat c	37
			strain energy E_{st}	30
			temperature scales	36
			thermodynamics	47
			volt V	44
			watt W	18

Study guide

This Unit consists of three parts—the Main Text, a radio programme and a TV programme. Each of these is about energy, a term which is frequently used in all branches of science, as you will see as you progress through the Course.

The text begins with three introductory Sections and an account of how energy can be measured. We then go on to discuss in detail some of the different forms of energy and conclude with some brief comments on the so-called 'energy crisis'. There are no Home Experiments associated with this Unit.

In the radio programme we show how important it is to account for the different energy conversions that take place in everyday life. Before you listen to the programme, you should try to have read the first two, introductory, Sections.

The TV programme deals with the more specialized topic of accounting for the energy inputs and outputs in two different cases, in a hydroelectric power station in Snowdonia and in an electric kettle. We discuss the different forms of energy that are converted and try to check the validity of the principle of conservation of energy. To derive the maximum possible benefit from this programme, you should have at least browsed through the Sections up to and including Section 10 (with the exception of Section 5), because in those Sections many of the terms that are used in the programme are introduced.

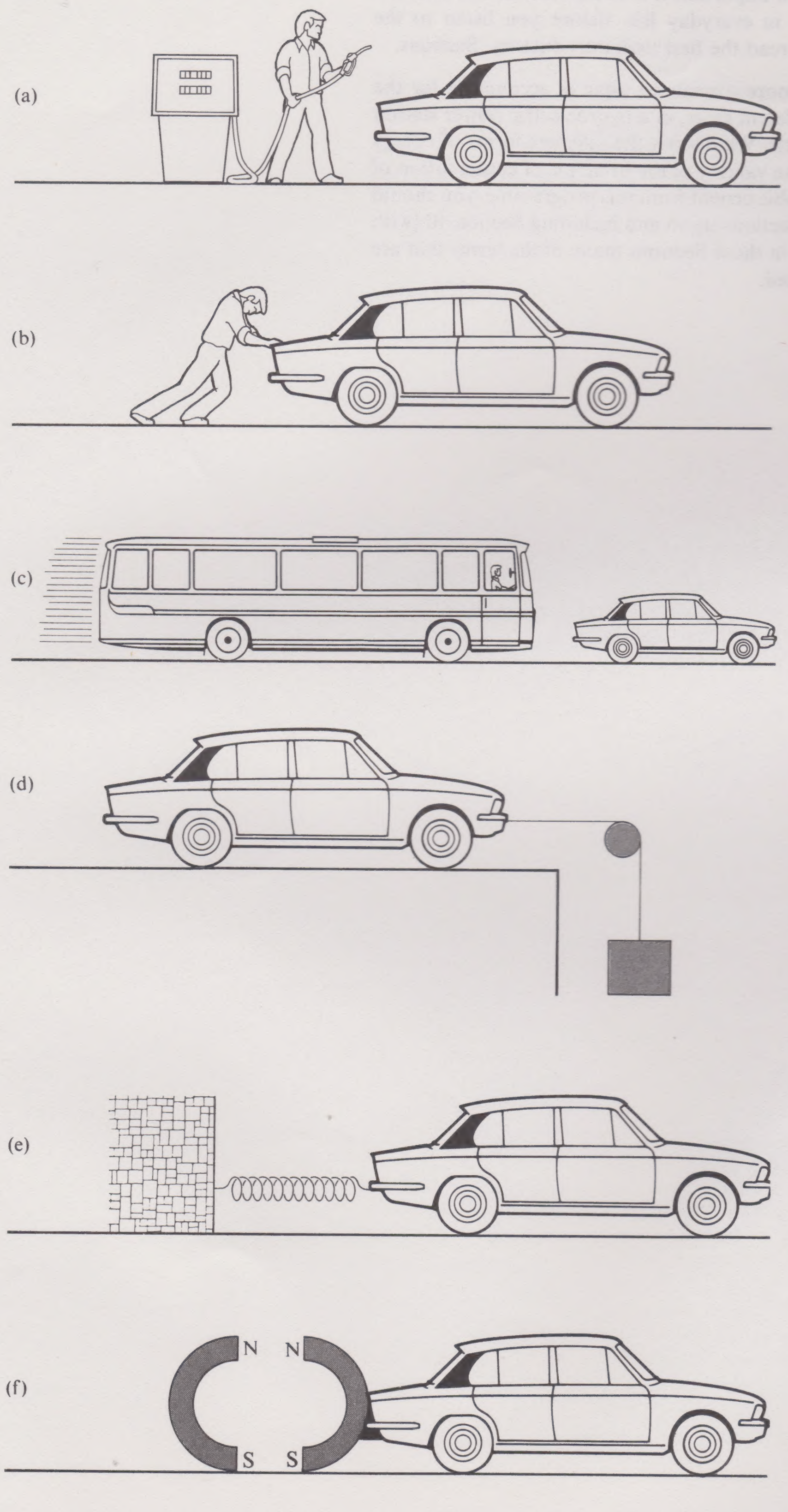


FIGURE 1 Different ways of getting a car to move along a road.

1 Introduction

In this Unit, you will be studying one of the most important concepts in science, namely, energy. You have already met the term in Unit 4, where it was used to describe the attribute of an earthquake that enables it to move land masses, and to demolish buildings and roads. Although the word energy is used frequently by scientists, it is notoriously hard to define precisely. However, you can get a rough idea of its meaning by examining what exactly is implied in everyday conversation when a person is said to be 'energetic'. You would agree that such a person has the capacity to *do* things, to influence events (and possibly other people) in one or more ways, although in which ways is not specified.

The meaning of energy in science is analogous to its colloquial meaning. Whereas a *person* is said to be energetic if he or she does things, in science a *physical system* (by which we mean an object or objects which are separated, in the mind's eye, from their surroundings) is said to be energetic if the objects in the system can do things and, possibly, affect other objects too. An example should make this rather abstract notion more clear: picture a person standing next to a football that is at rest on the ground—this is an example of a physical system.

physical system

The football can't do much harm sitting there minding its own business, yet the person could do things to the football to enable it to influence other objects. For example, it could be raised from the ground and dropped; when released it would fall and hit the ground with a thud. The person could also enable the football to influence other objects by kicking it, thereby setting it in motion. It could then break windows, move other footballs and do all manner of other things.

The point of all this is that the person has—in two different ways, by lifting it and by kicking it—enabled the football to affect its surroundings. In both cases, the football has been given *energy*. You may ask whether there are only two ways in which an object can be given energy—in fact, there are many more as you will see in the next Section.

2 Different forms of energy

In this Section, we shall discuss some of the many ways in which energy can be transferred to different objects. Perhaps the most visibly obvious form of energy is the one associated with a moving object. A car travelling along a road has a certain amount of energy—energy of motion, if you like. If you were to stand in its way, it would transfer some of its energy to you, probably with disastrous results. But from where does its energy of motion come? Or, to put the question another way, how can energy be transferred to the car to get it to move along the road?

Of course, the usual way is to pour some petrol into the car's tank and to drive it along the road (Figure 1a). If the car had broken down or there was no petrol available, you would have to roll up your sleeves and push it (Figure 1b).

There are plenty of other effective, though rather unorthodox, ways of doing the job. If you didn't care whether the car remained intact, you might drive a coach into the back of it (Figure 1c). But, if you preferred a less destructive method, then you could use the pulley system shown in Figure 1d—the car is attached to a suitably heavy weight which has been suspended over a pulley. When the weight is released, it falls and pulls the car along with it.

An even more unusual way of getting the car to move would be to squeeze a giant spring, to fix one end to a rigid wall with the other end pushing against the car. When the spring is released, it expands and pushes the car along the road (Figure 1e).

If you had a couple of large magnets handy, you could fix one of them to the rear bumper and bring the other towards it so that their north and south poles faced each other (see Figure 1f). The magnets would repel and the car would move along the road. Needless to say, you would have to be desperately short of petrol and muscle power before you would resort to *this* method but, in principle, it would work!

You can see that there are many different ways of getting the car to move. Each way is associated with a different form of energy that is being used to do the same job. It is convenient to give each form a name. For example, when the chemical petrol is used to move the car, we say that CHEMICAL ENERGY is being used and, when the car is physically pushed along the road we say, for obvious reasons, that MUSCULAR ENERGY is being used.

chemical energy

muscular energy

When the car is rammed by a coach, the aim is to transfer some of the coach's energy of motion to the stationary car. This 'energy of motion' is usually referred to as KINETIC ENERGY.

kinetic energy

In the next method, shown in Figure 1d, it is the GRAVITATIONAL ENERGY that is used to do the job. This form of energy is given this name because it is the gravitational force that pulls the weight downwards.

gravitational energy

When the spring is compressed, it is put under strain. When it is released, it returns to its original length and, in doing so, pushes the car forward. We say that the compressed spring has stored STRAIN ENERGY. Finally, in the case where magnets are used to get the car moving, we say, for obvious reasons, that MAGNETIC ENERGY has been used to do the job.

strain energy

magnetic energy

Now go back to Figure 1 and write next to each diagram the form of energy that is used to move the car. In each case, energy is transferred from something to the car and, in all but one of them, the energy is transformed in the process, that is, it is *converted* from one form into another.

energy conversion

In which case was there no energy conversion, only an energy *transfer*.

energy transfer

In Figure 1c, some of the kinetic energy ('energy of motion') of the coach was transferred to the car.

In all the other examples, energy was *converted* into kinetic energy from some other form of energy as well as being *transferred* to the car.

Since chemical, muscular, gravitational, strain and magnetic energy can all be transformed into the more easily visualized form of energy of motion, you may find it helpful to think of them as *energy of potential motion*. By that, we mean that the energy of the petrol (which doesn't look particularly energetic when it's in the car's tank) can potentially be converted to the energy of motion of a car. For its potential to be realized, of course, the petrol must be pumped to the engine which must be switched on. Similarly, you can think of the gravitational energy associated with a tile on a roof as energy of potential motion. You don't normally look at such a tile and think of it as having a lot of energy, but experience tells you that energy of motion is potentially available. Dislodge the tile and its energy of *potential* motion will rapidly be converted into energy of *actual* motion—and woe betide anybody who happens to be below when this potential for motion is fully realized.

energy of potential motion

energy of actual motion

To return to the example of the car, some time after it has been set in motion it comes to rest because of the friction in its bearings and the friction between its tyres and the road. What happens to the car's kinetic energy: does it vanish? In fact, it is converted into HEAT ENERGY—the road and also the car's bearings and tyres get warm. After a car has been on a long journey, you can feel how much warmer are its tyres compared with those of a car that has been standing still.

heat energy

You've now seen that there are quite a few different forms of energy. Before we go on to consider some more, check that you can identify the forms of energy in another example in which energy is being converted by doing SAQ 1.

SAQ 1 Have a look at Figure 2, in which a woman gymnast is shown jumping on a trampoline. In (a), she is descending through the air and, in (b), she falls on to the trampoline. She bounces back to a point at which she stops moving upwards (c) and then falls back down again to the trampoline. What forms of energy does she have in each of these cases?

There are many other forms of energy that we haven't yet mentioned, which cannot be used easily to get the car to move along a road, but which can nevertheless be used to do other jobs. Take, for example, the type of energy carried by earthquakes, the energy of seismic waves, which you first met in Unit 4. The havoc wreaked by earthquakes is a reflection of the vast amount of energy carried by

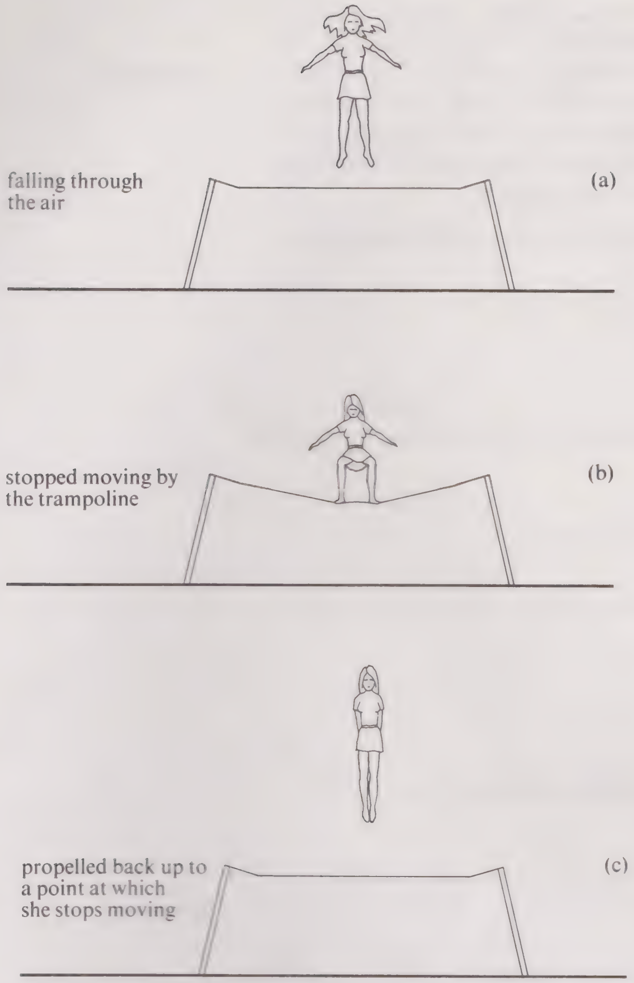


FIGURE 2 A woman gymnast bouncing on a trampoline.

them. But where does this energy come from? Rocks near the Earth's surface are subjected to stress until they fracture and the stored strain energy is converted into kinetic energy (energy of motion), which is then converted back into strain energy of the adjacent rocks. This energy is then converted into the energy of motion of the rocks, and so on, as the seismic wave travels through the Earth. What causes the stress on the rocks in the first place and what drives the great plates of the Earth's crust into collision with each other?

As we described in Units 6 and 7, the plate tectonic process is caused by *convection* of the asthenosphere and lithosphere near the Earth's surface—both have energy of motion (kinetic energy). This convection occurs because the interior of the Earth is much hotter than the Earth's surface. The heat energy of the Earth's interior comes from the slow release of energy from the radioactive decays of certain unstable elements (about which you will be learning more later in the Course). But where did *this* energy come from?

You should be getting the idea now that the story of energy conversions and transfers is one without a beginning and without an end. The answer to each of the questions, 'where did the energy come from?' or 'where does the energy go to?' raises a further question. In this plate tectonic process, you can see that energy is, at no point, created out of nothing or destroyed. *This is an example of the general principle that energy can neither be created nor destroyed in any conversion process.* We shall be returning to this idea in the next Section but, in the meantime, there are still some more forms of energy that we must consider.

Think about the simple household job of boiling a kettle of water. If you had a supply of gas (stored chemical energy) you could turn it on, burn it and so use the heat energy from the flame to boil the water. Alternatively, if you had a supply of electricity and an electric kettle, you could equally well do the job by using the ELECTRICAL ENERGY from the mains, by converting it first into heat energy and then transferring that heat energy from the heating element to the water in the kettle.

electrical energy

If the lid of the kettle is loose, then it will rattle (move about slightly) because of the pressure of the steam inside: some of the water's heat energy is converted into kinetic energy of the lid. You would hear the rattling, since SOUND ENERGY would be released; there are some kettles on the market which are designed to exploit this conversion of heat energy into sound energy. They are made so that when the water inside them boils, the steam rushes through a device which then whistles to tell you to turn off the electricity or gas supply.

sound energy

The kettle, therefore, converts its supply of energy into several different forms of energy as we have pictured in Figure 3.

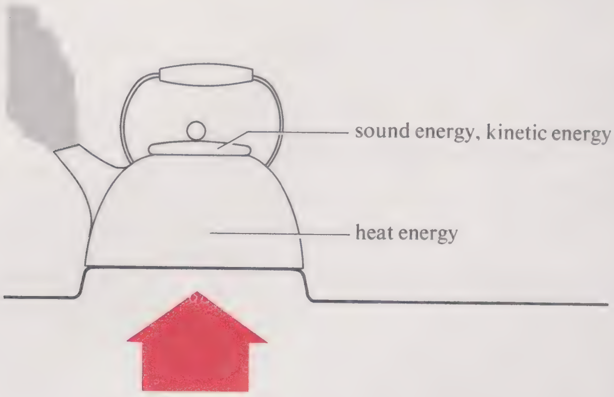


FIGURE 3 The energy conversions that take place in the boiling of water in a kettle.

There are just two more forms of energy that we want you to consider: the first of these is LIGHT ENERGY. This form of energy can, like any other, be converted into different forms of energy. There are plenty of examples of the conversion of light energy into chemical energy. This happens in every green plant as you will see when you study photosynthesis in Unit 24. At this very moment, light energy is being converted into chemical energy in your eye—that is how you are able to read the words on this page!

light energy

The last form of energy that we want to mention could be called MATTER ENERGY. If you could do an experiment with very accurate instruments to measure the masses of all of the material ingredients involved in a process in which one form of energy is converted into another, then you may find that the total mass of all of the materials *after* the energy conversion is very, very slightly less than the total mass of all the materials that were present *before* the conversion. The 'lost' mass has been converted to energy of the materials after the collision—matter energy has been converted to other forms of energy. This effect is so small that you could not hope to measure it in everyday processes, even with the most sensitive weighing balances, and so it is neglected for all practical purposes. However, there are some processes (which we shall discuss in more detail at the end of the Course) which go on in the Sun, in nuclear power stations and in nuclear explosions, where matter energy is converted to other forms of energy on a gigantic scale. The light energy that we receive from the Sun was converted from matter energy. This light energy was converted on Earth, over millions of years, to chemical energy which is stored in fossil fuels like coal and oil.

matter energy

In this Section, you have seen that there are many different forms of energy (Table 1) and that the forms can be converted into one another. Any process can be accounted for in terms of energy conversions, be it the boiling of a kettle of water, the moving of land masses by earthquakes, the flowering of a plant or the exploding of a nuclear bomb. Indeed, the Universe would remain still and unchanging were it not for the energy conversions that are taking place in it all the time.

Now try these SAQs, which test whether you can account for the energy conversions and transfers in two more simple cases.

TABLE 1 Some different forms of energy

Form	Examples of where the form of energy is found
GRAVITATIONAL	a weight lifted above the ground
KINETIC	any moving object
CHEMICAL	coal, gas, oil and petrol—these can be burnt in order to give heat energy
MUSCULAR	pushing a car along a road; kicking a football; walking
STRAIN	stored in a stretched rubber band and in a compressed spring
MAGNETIC	available when two magnets repel or attract each other
ELECTRICAL	available from an electric socket in the home
HEAT	a kettle full of hot water has more heat energy than one full of cold water
SOUND	can vibrate surroundings of a sound source, e.g. a loudspeaker
LIGHT	comes from the Sun and from an electric light bulb
MATTER	energy of the Sun; energy released in explosion of nuclear bombs; nuclear power.

SAQ 2 A child fires a stone with a catapult and it breaks a neighbour's window (Figure 4). Starting with the energy needed to stretch the rubber in the catapult, describe the energy conversions that take place in this lamentable incident.

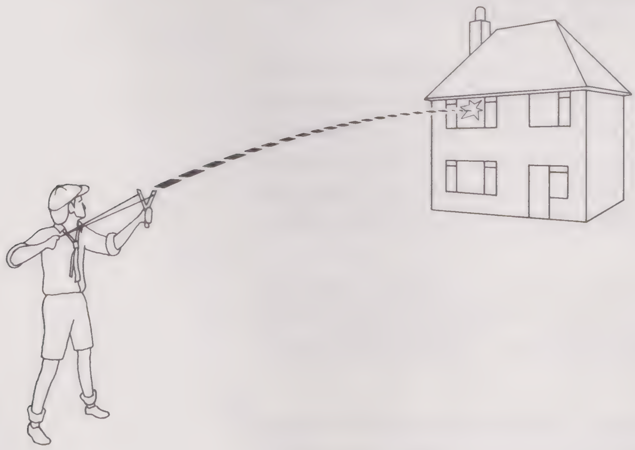


FIGURE 4 Catapulting a stone.

SAQ 3 Into which forms of energy does a standard household electric fire convert its supply of electrical energy?

3 Conservation of energy

3.1 Introduction

In the last Section, you saw that there are many different forms of energy and that energy can be converted from one form into others. The story of energy conversions is one without a beginning or an end—when an energy conversion occurs, the scientist should be able to say where that energy has come from and to account for the forms into which it is converted.

You may ask whether all this is useful; if all that you can do is to classify the different forms of energy, then surely you haven't learnt very much? But suppose that there is a way of predicting the total amount of energy that can be converted from a given energy supply, through some energy conversion—would not that be very useful? For instance, the question of how much fuel (stored chemical energy) is needed to drive a car for a certain distance is of obvious interest to motorists. They certainly would not expect to drive a thousand miles on a teaspoonful of petrol! In this Section, you will see that there is a principle which says how much energy can be obtained from the conversion of a given energy supply.

3.2 Energy is always conserved

Think, first of all, about whether energy can be created out of nothing, that is, whether it is possible to make available a certain form of energy (e.g. kinetic) without having converted (or transferred) some source of energy beforehand. We said in the last Section that energy *cannot* be created out of nothing—it can only be made available by some previous energy transfer or conversion.

You saw in the plate-tectonic process that at no point does energy disappear or appear from nowhere, and we said that this is true in *all* energy conversion processes. It turns out that whenever quantitative measurements are made of energy conversions, the *total amount of energy of a physical system* is the same before any conversion of energy as it is afterwards.* This is the principle of conservation of energy, one of the most important principles in science. Its usefulness lies in its ability to make *predictions* about the amount of different forms of energy that can be converted from an energy supply. As we shall describe later, it also allows energy to be quantified, that is, it allows us to give a common measure of energy that is applicable to all the different forms.

principle of conservation of energy

To see how the principle of conservation of energy allows predictions to be made about processes of energy conversion, take the particular example of the electrical energy supplied to your home. You can use this energy to heat and light your home and to run electrical gadgets and appliances. The electricity board keep a record of the number of units of electrical energy that you use and you can actually read off the number for yourself, by checking the reading on your electricity meter.

Suppose that you use one unit of electrical energy to run a fluorescent light, and exactly the same amount of energy to run a bulb with tungsten filament. You would find that the fluorescent light gave *more* light for your money than the one with the tungsten filament.

The principle of conservation of energy then *predicts* that at least one of the lights must have converted its supply of energy into another form of energy besides light energy. If they had both converted the one unit of electrical energy supplied to them *completely* to light energy then they would both give *the same amount* (one unit) of light energy. Is the prediction correct? Do the lights convert their supplies of electrical energy into any other form (or forms) of energy besides light energy?

If you have ever tried to remove a light bulb from its socket just after it has been switched off, you will know that it is very warm if it has been on for some time. Just as the principle predicts, the bulb does not only convert its energy supply into light energy—it converts some of its supply to heat energy.

* If you've forgotten the meaning of the term 'a physical system', turn back to Section 1, where it is defined.

The principle can also be used to find out *how much* heat energy is converted from the supply of energy if you know how much of the supply was converted into light energy. Suppose, for example, that you ran an ideal fluorescent light using, say 1 unit of electrical energy and that you found that it did not get hot at all—that all of its energy supply was converted to light energy (see Figure 5a). Then suppose you supplied the bulb with the tungsten filament with the *same* amount of electrical energy and found that you got 10 per cent as much light (0.1 unit) from it as you did from the fluorescent light. Then the principle of conservation of energy would tell you that the other 0.9 unit must have been converted to some other form of energy (see Figure 5b). This 0.9 unit should appear as heat energy. You can test this prediction by comparing the amount of heat energy that was converted from the supply by the bulb with the heat from some device which could be relied upon to convert 0.9 unit of electrical energy entirely into heat energy. You would be bound to find that the 0.9 unit was accounted for: no process has ever been witnessed in which energy was not conserved, to within the limits of experimental error.

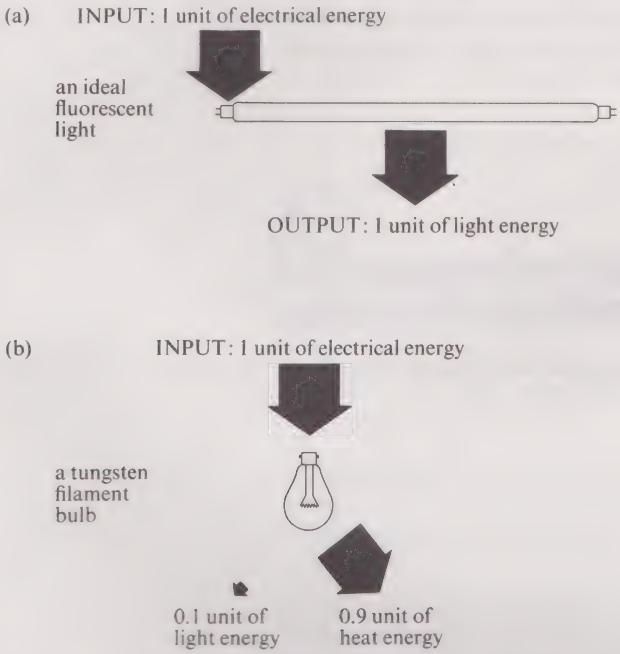


FIGURE 5 Comparison of the input and output of an ideal fluorescent light with that of a tungsten filament bulb. In both cases, the energy input = energy output.

We shall be applying this extremely important principle many times in this Unit and we shall often need to use it later in the Course. You would do well to read this Section again if you are still not clear about what the principle says and why it is important—the effort will be well worth while when you come to study in detail different forms of energy. If you find later in the Text that you don't understand why we are making such a fuss about the importance of the principle of conservation of energy, then you should come back to this Section to see how it allows us to make quantitative the notion of energy. *Without* this principle, energy would not be a useful concept and we should not have devoted a whole Unit to it!

4 Measuring energy

4.1 Introduction

In the last two Sections, you saw that there are many different forms of energy and that when they are converted into one another, there is no loss of energy in the process. Before you can go on to learn more about some of these different forms, you need to know how to calculate the amount of energy required to do a given job and, also, the units in which energy is measured. These are the subjects of this Section and of the next one.

4.2 The energy required to move objects

Think again about the problem of getting a car to move along a road. In this Section, we shall consider the problem of finding how much energy is required to pull the car along the road with a constant force: the slightly more complicated case in which it is moved by a *varying* force, will be dealt with in the next Section.

How much energy is required to keep the car moving with a constant force for a certain distance?

Experiments show that this energy depends only on the distance d travelled by the car and on the constant force F required to keep it moving. Is the energy required proportional to F multiplied by d, F^2 multiplied d, F divided by d, or what? The only way in which we can find out is by doing the appropriate experiments.

Look at the apparatus shown in Figure 6: a lorry is towing the car and there is a device between them which measures the force pulling the car along. This force is balanced by the frictional forces between the car and the road. Hence there is no net force on the car and, by Newton's second law (force = mass × acceleration), the car does not accelerate—its velocity remains the same.

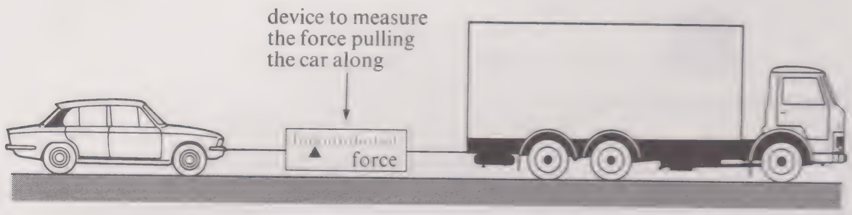


FIGURE 6 An experiment to measure how the energy required to pull a car along a road varies with the distance travelled and with the force that pulls it along.

The energy being used to tow the car is provided by the fuel (chemical energy) in the lorry's tank. The lorry requires a certain amount of fuel if it is to move. Hence, the energy required to move the *car* along is measured by the *extra* fuel consumed by the lorry in pulling the car.

To see how the energy required to pull the car along depends separately on the distance travelled and on the force, you would have to do two experiments: one to find out how the energy required varies with the distance that the car travels, and the other to see how it varies with the force that pulls it along.

In the first of these experiments, you would have to keep the force constant, so that you could be sure that any variation that you measured in the energy required to pull the car along had nothing to do with variations in the force. Similarly, in the second experiment, in which you want to find out how the energy required depends on the force that pulls the car along, you would have to keep constant the distance over which the car is pulled. Think about the first of these experiments.

Do you expect that the energy transferred to the car would increase or decrease with the distance that the car is pulled (with the force pulling the car kept constant)?

You should expect that the further the car is pulled, the more energy is required. In fact, experiments show that the energy E transferred to the car is directly proportional to the distance d that it travels (provided the force pulling it along is constant):

$$E \propto d$$

The second question is how much the energy required to pull the car along depends on the force pulling it along. The force could be varied by driving the vehicles over different types of road surface, or by applying the car's brakes.

Do you expect that the energy required to pull the car along would increase or decrease if the force pulling the car along were to *increase* (with the distance that the car is pulled kept constant)?

If the force were to increase, then the energy required to pull the car along should also be expected to increase. The results of experiments say that the energy transferred E is directly proportional to the force F (provided the distance that the car travels is kept constant):

$$E \propto F$$

So the energy E required to pull the car along is directly proportional to both F and d:

$$E \propto F \qquad \text{and} \qquad E \propto d$$

These two statements can be combined into one:

$$E \propto F \times d \tag{1}$$

that is, the energy required is proportional the product of the force and the distance travelled. This is true irrespective of the form of energy that is responsible for the moving of the car. Note that equation 1 can also be written as:

$$E = kFd \tag{2}$$

where k is a dimensionless constant of proportionality. The dimensions of energy can be obtained from this expression: they are simply the product of the force with those of distance. The former are [mass] × [length] × $[\text{time}]^{-2}$ and the latter are, by definition, [length]; so the dimensions of energy [E] are [mass] × $[\text{length}]^2$ × $[\text{time}]^{-2}$:

$$[E] = [\mathrm{MLT}^{-2}] \times [\mathrm{L}] = [\mathrm{ML}^2\mathrm{T}^{-2}]$$

One point that we ought to mention in passing is that some people speak of 'work done by the force' instead of 'energy transferred by the force', the term we have used here. Strictly speaking, there is nothing wrong with calling the energy transferred by a different name, but we prefer not to use the term 'work done' as it is best reserved for energy transferred by human beings. It may sound all right to say work done by a person in moving a car, but it certainly sounds peculiar to speak of 'work done' by chemical energy in moving it!

4.3 Units of energy

Equation 1 says that the units of energy are given by the product of the units of force with those of distance. You know from Section 3.4 of Unit 3 that the SI units of force are newtons and you should know that the SI units of length are metres. (From now on we shall not bother to remind you that we are using SI units.) So the unit of energy is the newton metre, which is usually referred to as the joule* and abbreviated to just J. The definition of the joule is that it is the amount of energy transferred by a force of 1 newton when it moves through a distance of 1 metre. This is the unit of all forms of energy.

joule J

This definition fixes the value of the constant of proportionality in equation 2 in the previous sub-Section. To see this, consider a constant force of 1 N acting over 1 m. According to equation 2, the energy E transferred by this force is given by:

$$E = k \times 1 \text{ newton} \times 1 \text{ metre}$$
$$= k \text{ newton metre}$$

But the definition of the joule says that $E = 1$ joule, so $k = 1$; that is, equation 2 becomes:

$$E = Fd \tag{3}$$

ITQ 1 A table is pushed 10 m along the floor by exerting a constant force of 50 N. How much energy is transferred to the table?

* This unit is named after the English physicist James Joule (1818–89) who did much important work on heat energy. In Section 8, we shall describe some of his work, including an experiment that he did on his honeymoon.

TABLE 2 The energy associated with . . .

energy/J	
10^{20}	A severe earthquake
	The explosion of a hydrogen bomb
10^{18}	
10^{16}	
10^{14}	
	Concorde flying from London to New York
10^{12}	
10^{10}	
10^{8}	The combustion of one gallon of petrol
	The heating of enough water for an adult's bath
10^{6}	The running of an electric fire for one hour
	The bringing on one pint of water to the boil from room temperature
	A saloon car moving at 30 m.p.h.
10^{4}	
10^{2}	
	The lifting of a 3 kg bag of potatoes to waist height
10^{0}	The stretching of a 0.1 m rubber band to three times its length
	The visible light from a domestic light bulb in one second
	An adult's shouting for one second
10^{-2}	
10^{-4}	
	An adult's talking normally for one second
10^{-6}	The beat of a fly's wing

How large an amount of energy is a joule? Have a look at Table 2, where the amounts of energy required in some different circumstances are listed. You can see that one joule is roughly the amount of energy required to stretch a 0.1 m rubber band to three times its natural length—if you have a rubber band of about this size you might like to stretch it, to see how it feels to transfer about one joule of your muscular energy.

You should be able to see from Table 2 the huge differences in the energy associated with different jobs. There is 10^{10} (ten thousand million) times more energy available from the combustion of a gallon of petrol than there is sound energy released when you shout for a second! Note also the huge amounts of energy liberated in an earthquake and in the explosion of a hydrogen bomb (a type of nuclear bomb).

Later on in this Unit, you will find out how to calculate the amounts of kinetic, gravitational and heat energy associated with different processes and you will be able to check for yourself some of the entries in Table 2 and be able to add some more examples of your own, if you so wish.

Although the joule will usually be used as the unit of energy in this Course, it is important to realize that there are other units which are in common use. Table 3 lists some of these units together with an indication of where they are used and the number of joules that are equivalent to one of these units. There is no need for you to memorize the contents of Table 3, but you should know that energy can be measured in different units and you should be able to convert from one set of units to another, using Table 3 or the Tables supplied in your *Science Data Book**.

You probably won't recognize the unit called the electronvolt, mentioned in Table 3. We shall be using this unit frequently when we discuss the structure of atoms later in the Course.

electronvolt eV

TABLE 3 Some units of energy in common use

Unit of energy	An example of where this unit is commonly used	The number of joules that are equivalent to this unit of energy
British thermal unit (Btu)	gas bills	1 Btu = 1.1×10^3J
kilowatt-hour (kWh)	electricity bills	1 kilowatt-hour = 3.6×10^6J
Calorie*	information about dieting	1 Calorie = 4.2×10^3J
erg	some scientific literature	1 erg = 10^{-7}J
electronvolt (eV)	in analysing the structure of atoms	1 eV = 1.6×10^{-19}J

* In some books, the unit of the calorie (with a *small* c) is used. This unit is equal to a thousand times less energy than the Calorie (with a capital C). 1 calorie = 4.2 J = 10^{-3} Calorie. However, in information on dieting, the Calorie referred to is *always* the one spelt with its first letter a capital C.

At this stage you should be able to:

(a) State the principle of conservation of energy and apply it to simple processes in which energy is converted from one form to another. (SAQ 4)

(b) Find the energy transferred to an object which is moved a given distance by a constant force. (SAQ 4)

(c) Recall that there are different units of energy and be able to use Table 3 to convert from one set of units to another. (SAQ 5)

To test that you have achieved these Objectives, try SAQs 4 and 5.

SAQ 4 Some people push a car smoothly along a road for 0.5 km and they exert a net constant force of 200 N to keep the car moving. How much energy do the people transfer to the car?

If they stopped pushing, the car would come to a halt if it were on level ground. In that case, to where has the energy gone that has been transferred to the car?

SAQ 5 (a) Suppose that electrical energy costs 3p per kilowatt-hour. How much does it cost per joule?

(b) It takes about 3.6×10^5 J of energy to run a standard household light bulb for an hour and about 2×10^7 J to heat enough water for an adult's bath.

According to these estimates, how much does it cost to run the light bulb for an hour and how much does it cost to heat the bath-water?

* Tennent, R. M. (ed.) (1971) *Science Data Book*, Edinburgh, Oliver & Boyd. You will find this book in your Home Experiment Kit.

4.4 Power

In sub-Section 4.2, we have shown how to calculate the amount of energy required to move something over a certain distance. This is of interest in everyday life; for example, motorists have to make sure that their cars have enough fuel before they go on a journey. At the same time, however, they need to know that the car can do the journey reasonably quickly. A car which is so worn out that it can only move at a snail's pace isn't much use if the passengers want to get to their destination in a hurry. This example shows that when energy is transferred in order to do a job, it is important to know both whether there is enough energy available and whether the energy can be converted quickly enough to do it in a reasonable time. The rate at which one form of energy can be converted into another is so important that it has been given a name—power:

power

$$\text{power} = \frac{\text{amount of energy converted}}{\text{time taken to convert energy}} \tag{4}$$

The units of power are simply the units of energy divided by the units of time—joules per second. Another name for this unit is the watt*, often abbreviated to just W.

watt W

$$1 \text{ watt} = 1 \text{ joule per second} = 1 \text{ Js}^{-1}$$

ITQ 2 Use the definition of the watt to prove that 1 kilowatt-hour = 3.6×10^6 J, as stated in Table 3.

Most electrical appliances are marked with their power-rating in watts, which tells you how quickly the device converts its supply of electrical energy into other forms of energy. When a light bulb is marked 100 watts, it means that it can convert 100 joules of electrical energy into other forms of energy in 1 second. (Remember from Section 3 that a light bulb converts its energy supply into both heat and light energy.)

Another common unit of power is the horsepower:

$$1 \text{ horsepower} = 746 \text{ watts}$$

This unit is usually used to describe the power rating of engines.

You should now be able to recall equation 4 and use it to calculate the amount of energy converted by a device in a certain time, given its power-rating. Check that you can do this by trying SAQ 6.

SAQ 6 An electric heater is rated at 1000 watts. Assuming that it converts 99 per cent of its electrical energy supply to heat energy, how much of the energy supply is converted into heat energy in five minutes?

5 The energy transferred by unevenly applied forces

In the last Section, you saw how to calculate the energy transferred by a force that is constant. The problem is that, in everyday life, when you move something bulky like a chair, you usually move it jerkily—something may stop you from moving it along smoothly by getting in your way, or else you may pause because you're tired. In any case, you rarely transfer your muscular energy at a constant rate.

As we promised at the beginning of the last Section, we shall now describe how to find how much energy is transferred by a varying (non-constant) force.

We shall consider the particular example, shown in Figure 7, of the force between a locomotive and the first coach that it pulls along. The locomotive burns diesel fuel which has stored chemical energy, and some of this energy is transferred to

* This unit is named after James Watt (1736–1819), the Scottish engineer who is famous for the major part that he played in developing the steam engine.

the first coach via the coupling between them. The force in this coupling varies when the locomotive changes speed and when it goes up and down hills. How can we find the amount of energy that is transferred to the first coach by the force in the coupling?

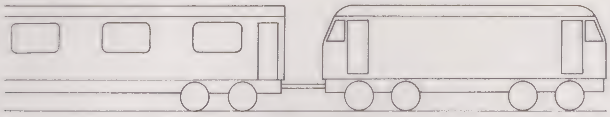


FIGURE 7 A simple example of a situation where the force is variable.

Since the amount of energy transferred to the first coach depends on the force in the coupling and on the distance that the train moves, both of these quantities must be measured. In practice this is done by installing two devices in a test car between the locomotive and the first coach, as shown in Figure 8. The first of these devices, a force meter, measures the magnitude of the force in the coupling in units of kilonewtons, that is in units of thousands of newtons. The second device, a distance meter, measures the distance that the train travels in units of kilometres. The readings from each of these devices can be seen on digital displays in the test car, and these are also shown in Figure 8.

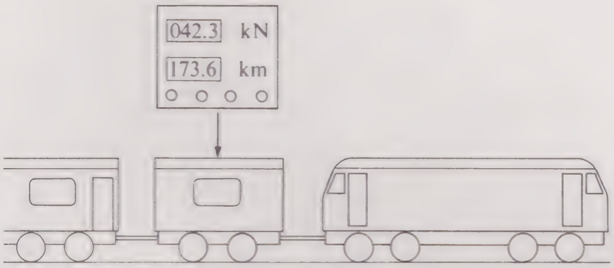


FIGURE 8 The test car contains devices that measure force and distance.

Consider first the simple case in which the train is travelling along a level track at a constant velocity, so that the force measured in the test car is constant. As the train moves along, the reading on the distance meter increases but the reading on the force meter remains constant. You can see a simple example of this in Figure 9. There the force in the coupling is always 20 kN, and the train travels 5 km between the two instants shown.

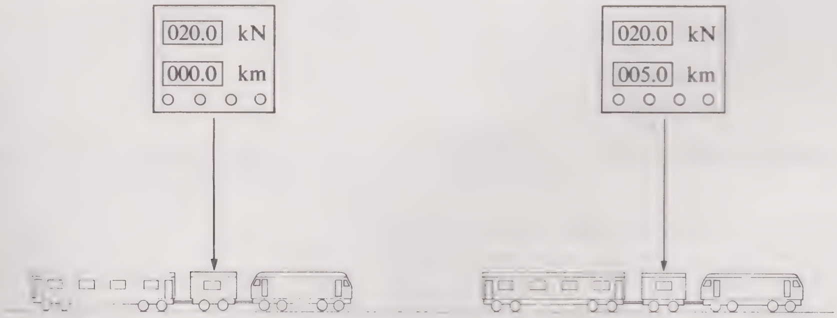


FIGURE 9 The digital displays at two separate instants. The force has remained constant.

One way to record this information is to draw a graph of the force in the coupling against the distance travelled, as shown in Figure 10. Since the force is constant, it is represented by a horizontal straight line on the graph.

Now consider the shaded rectangular area shown on the graph. Its height represents the magnitude of the force in the coupling, which is 20 kN, and its base represents the distance that the train travels, which is 5 km. The area of the

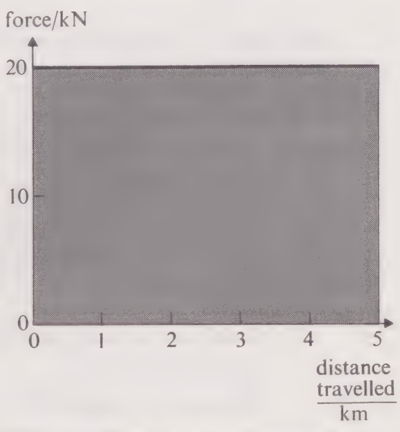


FIGURE 10 A graphical record of the information from the digital displays of force and distance.

rectangle is simply the product of its height and its base, that is the product of the force in the coupling and the distance that the train travels. So:

$$\begin{aligned} \text{shaded area} &= \text{constant force} \times \text{distance travelled} \\ &= (20\,\text{kN}) \times (5\,\text{km}) \\ &= (2 \times 10^4\,\text{N}) \times (5 \times 10^3\,\text{m}) \\ &= 10^8\,\text{N m} = 10^8\,\text{J} \end{aligned}$$

What does this area represent? (Refer back to equation 3 in sub-Section 4.3 if you are unsure.)

The area is the product of force and distance and, as you saw in sub-Section 4.3, this product is the energy transferred by the constant force.

We can conclude, therefore, that for a *constant* force the amount of energy transferred is represented by the area under the graph of force plotted against distance.

We shall now use this result to find the energy transferred when the force is *not* constant. Picture this time a train travelling along a track in such a way that the force between locomotive and first coach *varies*. The graph in Figure 11 represents such a situation. At the beginning of the journey the force in the coupling is 5 kN, and this force increases smoothly to 19 kN as the train moves along the track. The force then decreases to 2 kN. The question that we want to answer is 'how much energy has been transferred to the first coach by the force in the coupling over the distance of 10 km that the train travels?'

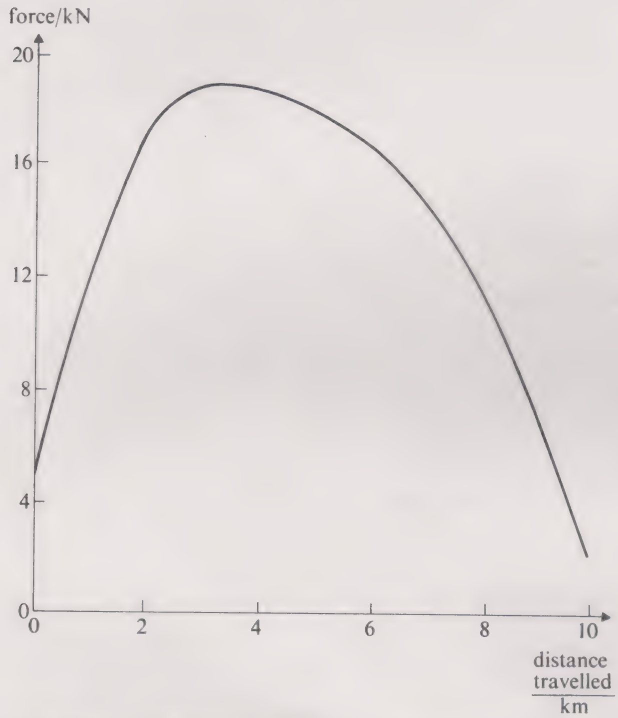


FIGURE 11 The graphical record of a journey in which the force changes.

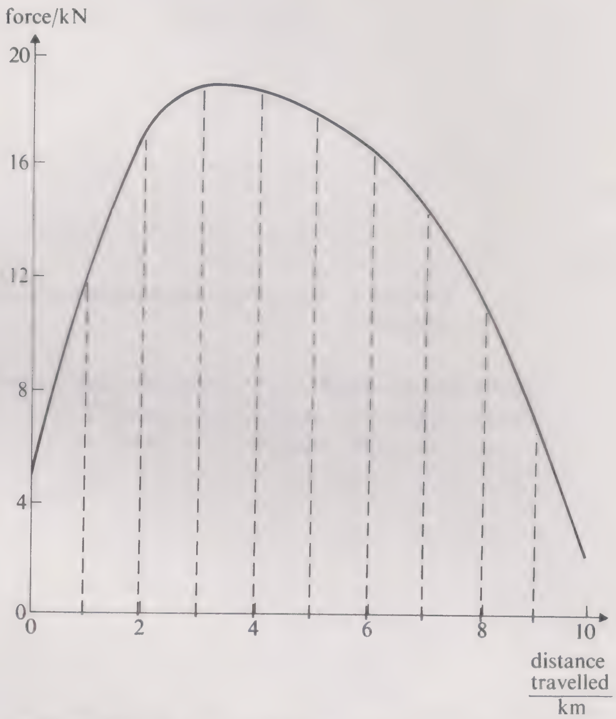


FIGURE 12 The graph in Figure 11 divided into short distances $l(= 1\,\text{km})$.

The way to solve this problem is to divide the distance travelled by the train into equal, short distances l, as shown in Figure 12, and to consider each short distance separately. Let us start with the first short distance, and the force-distance graph for this is shown in Figure 13a. Now, although the force changes over this short distance, we can approximate it by the average force F_1, which is shown in Figure 13b. You can think of this average force as the average reading of the force meter on the first stretch of track.

How much energy is transferred by a constant force F_1 over a stretch of track of length l?

The energy transferred is $F_1 l$—the force multiplied by the distance.

How is the energy transferred related to the graph in Figure 13b?

It is represented by the shaded area under the horizontal line.

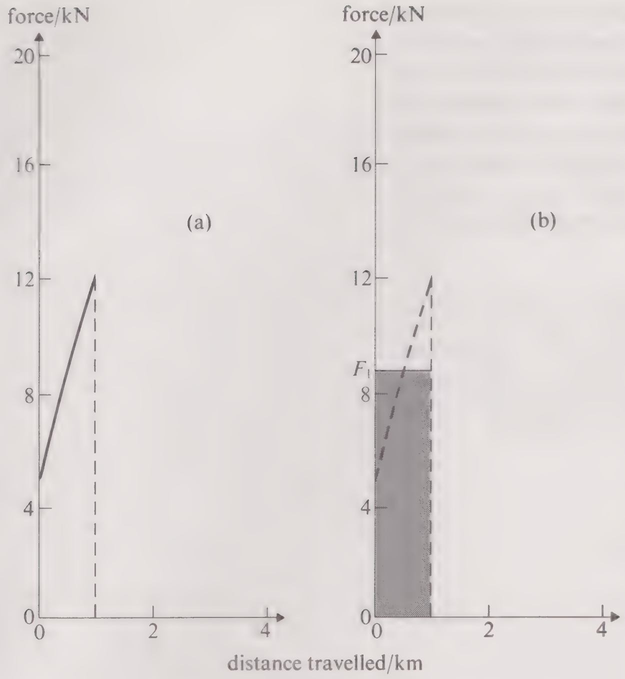


FIGURE 13 (a) The actual force acting over the first stretch of track can be approximated by (b) which shows the average force.

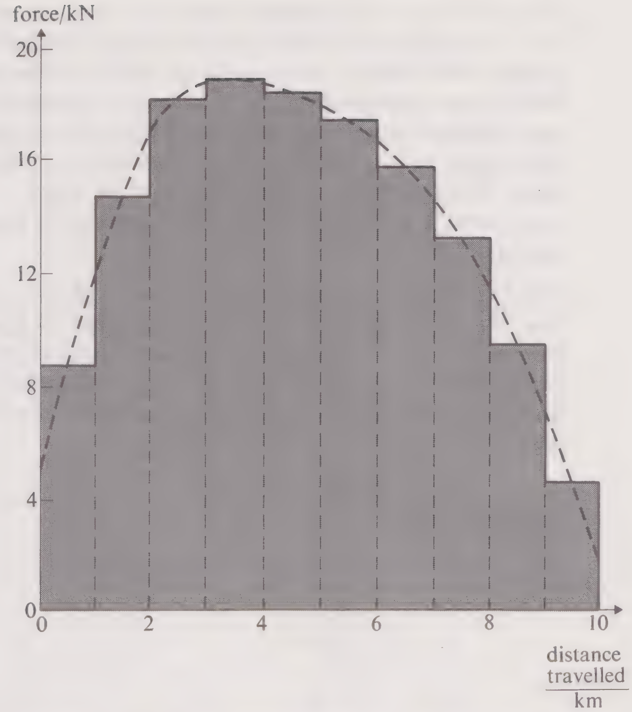


FIGURE 14 An approximation to the actual force–distance curve. In this approximation, the energy transferred is represented by the shaded area.

This argument can be repeated for each of the distance intervals shown in Figure 12. The varying force in each interval is replaced by the average force acting over that distance and, as a result, the smooth curve of Figure 12 is replaced by the stepped curve shown in Figure 14. Now the energy transferred during each distance interval (where the force is assumed constant) is represented by the area of the corresponding narrow rectangular strip. So the total energy transferred in the 10 km trip is represented by the sum of the areas of all of the strips, and this, of course, is just the shaded area under the stepped curve in Figure 14.

Fortunately for the passengers, trains do not generally travel in the jerky way indicated in Figure 14. We can make better approximations to the actual motion by dividing the trip into smaller distances, in each of which the force is constant. In Figure 15a, the distance intervals are 500 m and, in Figure 15b, they are 250 m.

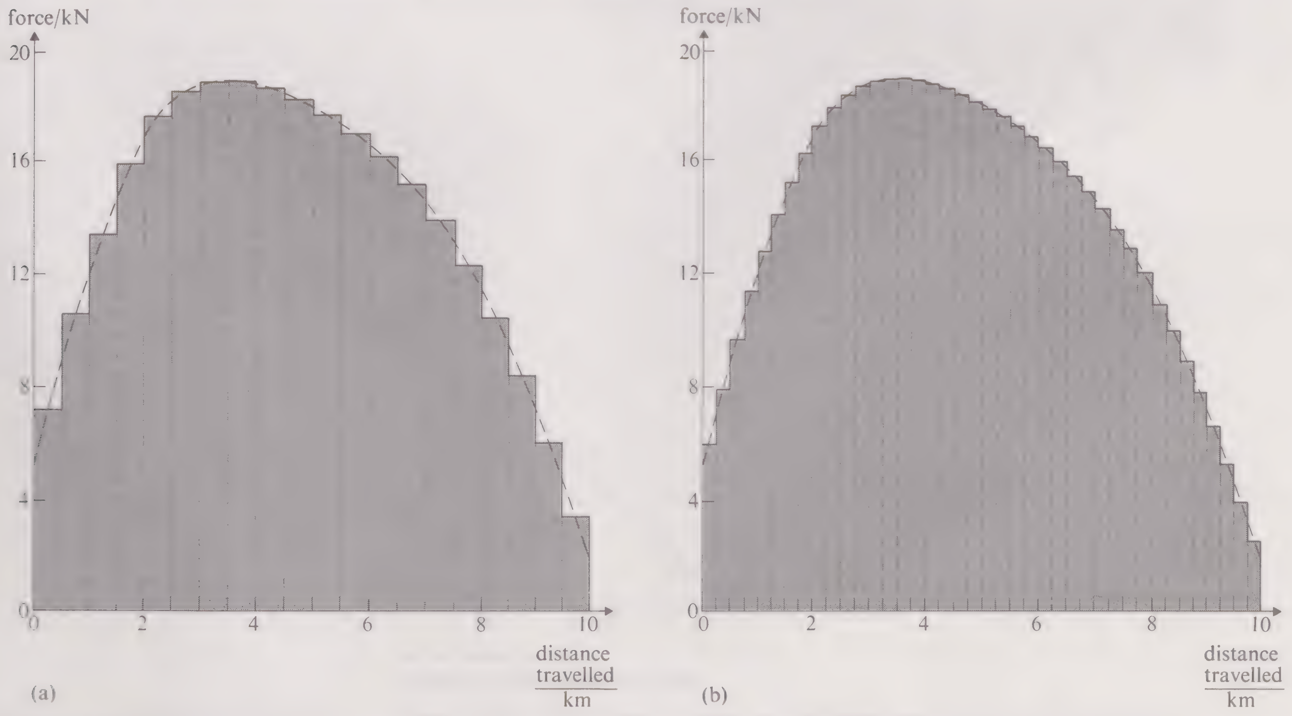


FIGURE 15 The same force–distance curve as in Figure 14 divided into smaller distance intervals.

You can see that as the distance intervals get smaller, the stepped curve represents ever more closely the actual motion of the train. What is more, the area under the stepped curve becomes more nearly the same as the area under the smooth curve. But we have already shown that the energy transferred when a force varies in the way indicated by the stepped curve in Figure 14 is represented by the area under the stepped curve, and this must be true however small the distance intervals are made. The conclusion, therefore, is that *the energy transferred by a smoothly varying force is also represented by the area under the smooth curve of force plotted against distance.*

This is an important result, and it applies to all force–distance graphs, whatever their shape. For example, the graph in Figure 16 represents the way that the gravitational force on a rocket decreases with its distance from the centre of the Earth. So the shaded area under this curve represents the energy required to move the rocket away from the Earth against this gravitational force—that is the energy required to launch the rocket into space.

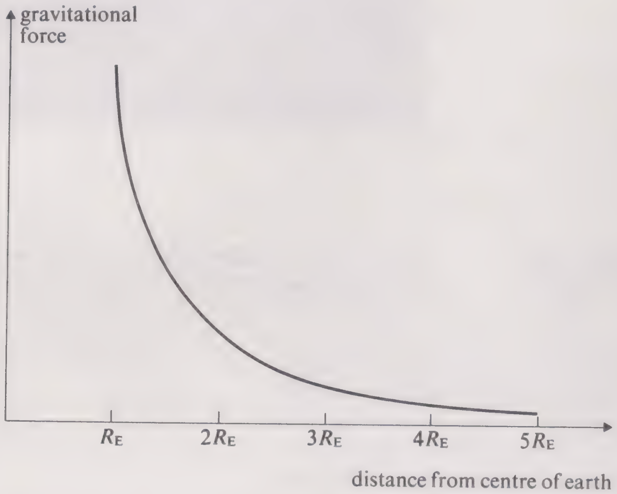


FIGURE 16 The gravitational force on a rocket. R_E is the radius of the Earth.

Now try SAQ 7, to test your ability to find the energy transferred to an object, given a graph of the force acting on it plotted against the distance that it moves.

SAQ 7 Someone pushes an object along the floor for 5 m by applying a varying force. The way in which the force acting on the object varies with the distance it travels is shown in Figure 17.

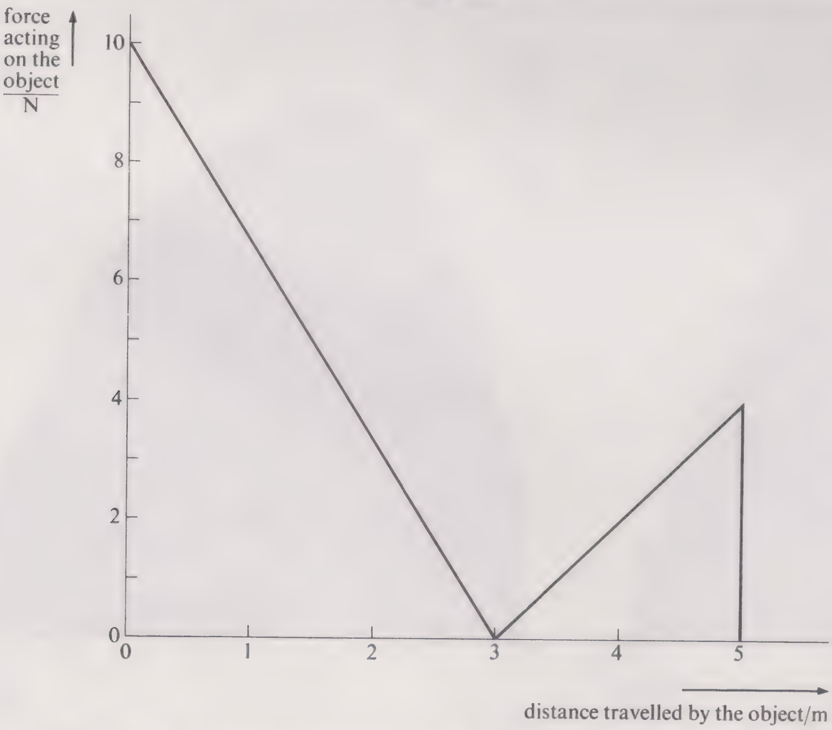


FIGURE 17 Graph of the force acting on an object plotted against the distance that the object moves.

Calculate the energy transferred by the force in pushing the object along. Then describe the action of the force in your own words (say when it is decreasing, increasing, etc.).

6 Kinetic energy

6.1 Introduction

You now know quite a lot about energy. In the preceding Sections of this text you have learned, first, that it comes in many different forms, secondly, that it is always conserved when it is converted from one form to another and, thirdly, that the energy required to move something can easily be calculated.

In the next few Sections, you will be using this knowledge to study some of the different forms of energy in detail. We begin with kinetic energy.

6.2 On what does the kinetic energy of an object depend?

We said in Section 2 that kinetic energy of an object is its 'energy of motion'—anything that moves has this form of energy.

On what does this form of energy depend? On the object's mass, acceleration, density, velocity or what? To make a start at answering these questions, ask yourself which you think has the more energy, a cannon-ball moving at $20\,\mathrm{m\,s^{-1}}$ or a pea, shot from a pea shooter, moving at the same velocity. You know that it would be much easier for you to withstand the impact of the pea, since it is much lighter than the cannon-ball. It is, therefore, reasonable to assume that an object's kinetic energy should depend on its mass, in such a way that the greater the object's mass, the greater its kinetic energy (at the same velocity).

Next, ask yourself whether you would mind as much if you were struck by the cannon-ball if it were moving very slowly, say at $0.1\,\mathrm{m\,s^{-1}}$, as you would if it were shot from a cannon. If you care as much about self-preservation as most people do, then you would certainly prefer the former. The slow-moving cannon-ball has less kinetic energy than a fast-moving one. But the kinetic energy of the cannon-ball should not depend on the *direction* in which it is moving—it has just as much kinetic energy when it is moving at $0.1\,\mathrm{m\,s^{-1}}$ upwards as it has when it has when it is moving at $0.1\,\mathrm{m\,s^{-1}}$ sideways, downwards or in any other direction for that matter. In other words, the kinetic energy of an object should depend on its *speed* rather than on its velocity.

In what way does the kinetic energy of an object depend on its mass and on its speed? We shall answer this question next.

6.3 How to work out the kinetic energy of a moving object

Picture an object, of mass m, at rest on the ground at point A (Figure 18). Now suppose that it is pushed by a constant force along to point B, distance d away, where its speed is, say, v. To find out how much kinetic energy the object has when it reaches B, the principle of conservation of energy must be used.

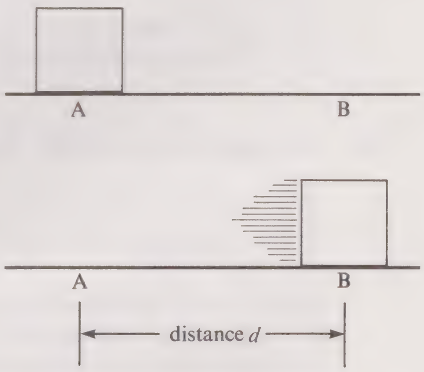


FIGURE 18 An object accelerated from A by a constant force F over a distance d in time t. Its speed when it reaches B is v.

Take the ideal case, in which there is no friction between the object and the ground and the atmosphere around it, in which case all of the energy transferred to the object is converted into kinetic energy. The principle of conservation of energy then says that the energy supplied to the object should be exactly equal to its kinetic energy. If you know the constant force acting on the object and the distance that it has travelled, then you know from Section 4 how to calculate the energy that must have been transferred to the object, that is, how much energy has been converted to the object's kinetic energy. You simply have to multiply the (constant) force by the distance that the object travels.

Which law relates the acceleration of the object to the force applied to it?

Newton's second law, which was first introduced in Unit 3. This says that:

$$\text{force applied} = \text{mass} \times \text{acceleration}$$

Given that the object's speed increases from 0 to v in time t, what was the magnitude of the force which must have been applied to it?

The acceleration, a, is given by the change in the speed divided by the time taken for the change to take place, t:

$$a = \frac{v - 0}{t} = \frac{v}{t} \qquad (5)$$

So, by Newton's second law, the force that must have acted on the object is

$$F = ma = \frac{mv}{t} \tag{6}$$

How much energy must have been transferred to the object by the force F in time t?

The energy E transferred is the product of the constant force F and the distance travelled.

$$E = F \times d = \frac{mvd}{t} \tag{7}$$

The energy E transferred to the object has been completely converted into the kinetic energy of the object when it has reached B—so from now on we shall write E as E_k.

Is there some way of relating the distance travelled by the object to the time during which it is accelerating? Back in Unit 3, you met a way of finding the distance travelled of a body that has *constant* acceleration (like the one we are considering here) Can you remember the way described there?

The distance travelled by the object is equal to its average speed multiplied by the time it takes to do the journey. If you don't remember this, then look back to Section 5.1.2 of Unit 3.

The speed of the present object increases uniformly from zero to v, so its average speed is $v/2$. Consequently, the distance d that it travels in time t is $(v/2) \times t$. Putting $d = vt/2$ in equation 7:

$$E_k = \frac{mvd}{t} = \frac{mv}{t} \times \frac{vt}{2}$$

$$E_k = \tfrac{1}{2}mv^2 \tag{8}$$

kinetic energy E_k

This is a beautifully simple expression for the kinetic energy which involves only the mass m of the object and its speed v.

You may remember that we argued that the kinetic energy should depend in some way on these quantities in sub-Section 6.2. By insisting that the kinetic energy of the object must be equal to the energy $F \times d$ transferred to it, we were able to deduce that $E_k = \frac{1}{2}mv^2$; the derivation depended explicitly on the assumption that the principle of conservation of energy is correct. In the next sub-Section, we shall use the results of an experiment to verify the assumption.

ITQ 3 Show that the dimensions of the expression on the right-hand side of equation 8 are correct.

6.4 An experiment to verify the principle of conservation of energy

Now that we have derived an expression for the kinetic energy of the moving object, you ought to check that it is right by doing an experiment. The question is, which experiment?

Picture a collision between two 10p coins, pushed towards each other on the top of a table. The coins certainly have kinetic energy because they are moving, although some of this energy will be converted into heat energy because of the friction between them at the point of collision and between them and the surface of the table. The coins stop moving when all of their kinetic energy has been converted into heat energy*.

Now suppose that there is some way of reducing this friction to such an extent that it can be ignored. Then the coins would only have kinetic energy, so that the principle of conservation of energy would predict that the total kinetic energy of the balls *before* the collision is exactly the same as their total kinetic energy after it. This type of collision is usually described as being 'elastic'.

elastic collision

* If you find it hard to believe that friction between the coins and the table causes the coins' kinetic energies to be converted into heat energy, then try rubbing your thumb firmly on some rough surface. You will soon find that your thumb gets warm as the energy supplied to it gets converted into heat energy.

You can now test this prediction yourself by using results from an experiment done with apparatus which has been specially designed to minimize the loss of kinetic energy to heat energy. This is done by propelling two objects towards each other on a cushion of air—this effectively cuts out the friction between them and the table. Each object has a spring attached to its end; during the collision, the springs store the kinetic energy of the objects as strain energy, which can then be converted back into kinetic energy. This process is illustrated schematically in Figure 19.

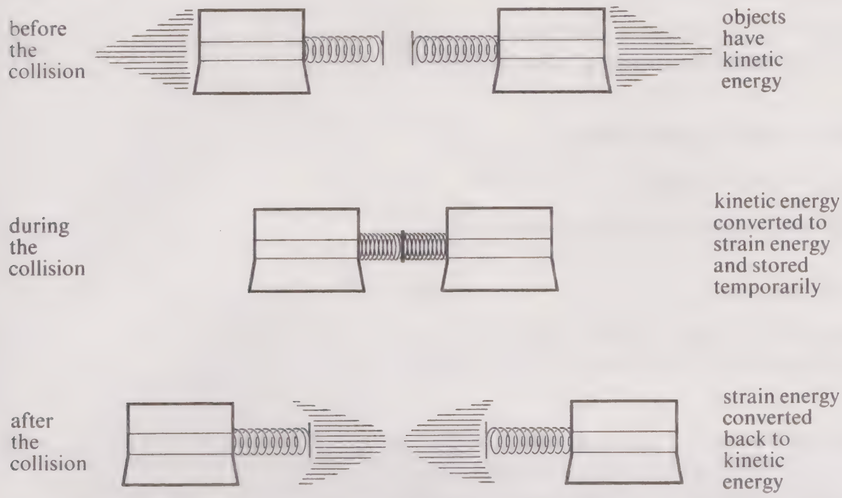


FIGURE 19 An elastic collision between two objects on a cushion of air.

A photograph of the apparatus is shown in Figure 20a—the objects are labelled A and B, and the springs on their ends are labelled S. The objects move on a track which constrains them to move along a straight line, LM, on a cushion of air. Note that each object has a small, triangular reflecting shape, R, mounted above it.

What do you need to know about the collision to check that kinetic energy is conserved? You need to know the masses and speeds of the objects, as their kinetic energies depend only on these quantities. We have arranged that their masses are the *same* and shall denote this mass as m.

(a)

FIGURE 20 (a) Photograph of the two objects A and B before they are set in motion along the straight line LM. The triangular reflector mounted above each object is marked R and the spring attached to one of each object's ends is marked S.

(b) Strobe photograph of the collision.

(b)

The following symbols denote the speeds of the two objects, A and B, before and after the collision.

speed of A before the collision $= u_A$

speed of B before the collision $= u_B$

speed of A after the collision $= v_A$

speed of B after the collision $= v_B$

The principle of conservation of energy says that the total kinetic energy of A and B before the collision are the same as their total kinetic energy after it (since the objects only have kinetic energy):

$$\text{total } E_k \text{ before collision} = \text{total } E_k \text{ after collision}$$

$$\tfrac{1}{2}mu_A^2 + \tfrac{1}{2}mu_B^2 = \tfrac{1}{2}mv_A^2 + \tfrac{1}{2}mv_B^2 \qquad (9)$$

This equation can be simplified by dividing each term by the common factor of $\frac{1}{2}m$:

$$u_A^2 + u_B^2 = v_A^2 + v_B^2 \qquad (10)$$

In words, this equation says that the *sum of the squares* of the speeds of A and B (which have equal mass) before the collision is equal to the sum of the squares of their speeds after it.

Now to check this prediction. To measure the speeds of A and B before and after the collison, we shall use the technique of strobe lighting that you met in Unit 3. With this technique, the speed of an object is measured by observing the distance d it travels between the flashes of the stroboscope, which occur at known, regular intervals t:

$$\text{the average speed of the object between two consecutive flashes} = \frac{d}{t} \qquad (11)$$

In Figure 20b there is a strobe photograph of A and B moving towards each other on the track before and after the collision—the light of the stroboscope flashes every 0.25 s. It was arranged that the reflecting triangular shape mounted above the object should fall during the collision, to make it easy to measure the speeds of A and B both before and after they collide.

We have measured u_A, u_B and v_A from the photographs and have left it to you to measure v_B, using equation 11. We recommend that you measure the average speed that B travels over 0.5 s after the collision. To find the distance travelled in that time, you need to measure with a rule the distance traveled by the reflecting shape. The scale of the photograph is that 1 : 4.8, that is 1 cm on the photograph is equal to 4.8 cm (4.8×10^{-2} m) actual size.

After you have entered your result, with its experimental error, on Table 4, calculate the square of v_B and see whether equation 10 is satisfied.

TABLE 4 Results of an experiment with colliding objects

$$u_A = \frac{(1.15 \pm 0.05) \times 4.8 \times 10^{-2}\,\text{m}}{0.5\,\text{s}} = (1.10 \pm 0.05) \times 10^{-1}\,\text{m}\,\text{s}^{-1}$$

$$u_B = \frac{(2.40 \pm 0.05) \times 4.8 \times 10^{-2}\,\text{m}}{0.5\,\text{s}} = (2.30 \pm 0.05) \times 10^{-1}\,\text{m}\,\text{s}^{-1}$$

$$v_A = \frac{(2.35 \pm 0.05) \times 4.8 \times 10^{-2}\,\text{m}}{0.5\,\text{s}} = (2.26 \pm 0.05) \times 10^{-1}\,\text{m}\,\text{s}^{-1}$$

$$v_B =$$

$$u_A^2 = (1.21 \pm 0.11) \times 10^{-2}\,\text{m}^2\,\text{s}^{-2}$$

$$u_B^2 = (5.29 \pm 0.23) \times 10^{-2}\,\text{m}^2\,\text{s}^{-2}$$

$$v_A^2 = (5.11 \pm 0.23) \times 10^{-2}\,\text{m}^2\,\text{s}^{-2}$$

$$v_B^2 =$$

$$u_A^2 + u_B^2 = (6.50 \pm 0.25) \times 10^{-2}\,\text{m}^2\,\text{s}^{-2}$$

$$v_A^2 + v_B^2 =$$

Do your results confirm that the principle of conservation of energy is correct in this case? If not, turn to Appendix 1, where you can check your results against ours, which vindicate the principle within the limits of experimental error.

The principle of conservation of energy led us earlier on to derive $E_k = \frac{1}{2}mv^2$, and you have now shown that this quantity is indeed conserved in an elastic collision, just as the principle predicts. This example shows that, in this case, the principle is self consistent.

All through this Unit, and indeed through the Course, you will be meeting energy conversions in which we shall assume that the energy is conserved. You will be pleased to hear that we shall not ask you each time to verify that this is true, as we did in the experiment that we have just described. But we shall ask you to accept that if an experiment *were* done to test energy conservation, then it would always be successful. The best reason for believing us is that no one has ever done an experiment that has disproved the principle!

6.5 An aside—the principle of conservation of momentum

Kinetic energy is not the only quantity which is conserved in an elastic collision. The total momentum of two objects is also exactly the same before the collision as it is afterwards. This is the *principle of conservation of momentum*, which is valid for *any* collision, not only elastic ones.

You first met this important principle in the TV program associated with Unit 3 (TV03) when we demonstrated an experiment that verifies it. In this sub-Section you can verify the principle for yourself, by using the data on the collision between A and B shown in Figure 20(b).

What is the momentum p of an object of mass m, travelling with velocity v?

The momentum $p = mv$ as we first said in Unit 3.

Notice that the momentum of an object depends on its *velocity* rather than on its speed, and that we have used the same letter v to denote the object's velocity as we used to denote its speed.

For the collision of the equal masses A and B, which is shown in Figure 20, the principle of conservation of momentum says:

$$mu_A + mu_B = mv_A + mv_B$$

Dividing through by m:

$$u_A + u_B = v_A + v_B \tag{12}$$

The principle says that for this particular collision between equal masses, the sum of the velocities of A and B is the same before the collision as it is afterwards. You should now use the data in the Table of results to check this relation. If you do not find that the relation is satisfied, turn to the Appendix 1, where you can compare your results with ours, which show that equation 12 is correct within the limits of experimental error.

We shall return to consider further the principle of conservation of momentum in Unit 29, when we shall apply it to the interaction of light with electrons. The principle of conservation of momentum is just as valid for these collisions as it is for the sort of collisions between really massive objects that we meet in everyday life.

Now that you have finished this Section you should be able to:

(a) Recall that the kinetic energy of an object $E_k = \frac{1}{2}mv^2$ and, given any two of the quantities E_k, m and v, be able to calculate the third. (SAQ 8)

(b) Recall that E_k is conserved in elastic collisions and be able to use this fact to solve simple problems on this type of collision. Also, recall that the total momentum of two objects is the same before the collision as it is afterwards. (SAQ 9)

To check that you can achieve these Objectives, try these SAQs.

SAQ 8 How fast would a bullet of mass 2×10^{-3} kg have to be moving if it were to have the same kinetic energy as an athlete (whose mass is 50 kg) who runs at $10\,\text{m}\,\text{s}^{-1}$?

SAQ 9 Consider the collision of two objects X and Y (see Figure 21). The speed of X before the collision is $8\,\mathrm{m\,s^{-1}}$ and that of Y is $2\,\mathrm{m\,s^{-1}}$ in the directions shown in the Figure. They collide elastically and the speed of X after the collision is $(16/3)\,\mathrm{m\,s^{-1}}$ in the direction shown in the Figure. If the mass of X is half the mass of Y, what is the speed of Y after the collision?

Name a quantity other than kinetic energy which would be conserved in the collision.

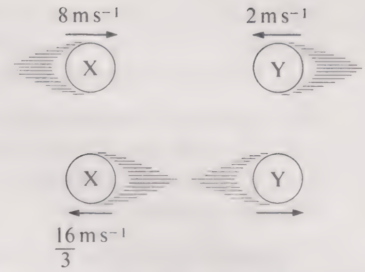


FIGURE 21 Elastic collision between two objects X and Y.

7 Gravitational energy

7.1 Introduction

In the last Section, the principle of conservation of energy enabled us to show how the kinetic energy of an object depends on its mass and its speed. We are now going to use the principle to work out how much gravitational energy any object has when it is lifted a certain distance above the ground. Then we shall use this knowledge to study a process in which kinetic energy is converted into gravitational energy (and vice versa).

7.2 How to calculate the gravitational energy of an object

Think about the job of lifting off the ground a heavy weight like a sack of potatoes, or a heavily laden shopping bag. In lifting these, all you are really doing is converting your own muscular energy to the gravitational energy of the object that you are lifting. You know that a light weight is easier to lift the same height off the ground than a heavy one and that it is easier to lift a given weight an inch off the ground than it is to lift it to shoulder height. These observations make it reasonable to suggest that the gravitational energy of an object depends on its weight and on the height to which it is lifted. To find out how the gravitational energy depends on these quantities, the principle of conservation of energy has to be used once again.

Look at Figure 22, in which someone is lifting a weight off the ground. The principle of conservation of energy says that:

$$\left\{\begin{array}{l}\text{energy transferred}\\ \text{to the object in}\\ \text{lifting it}\end{array}\right\} = \left\{\begin{array}{l}\text{gravitational}\\ \text{energy}\\ \text{given to object}\end{array}\right\}$$

The gravitational force acting on the object is, to all intents and purposes, *constant* over short distances, as you learned in Section 6.1 of Unit 3. So, to find the energy transferred to the object, all you have to do is multiply this constant force by the distance through which it moves the object.

$$\left\{\begin{array}{l}\text{energy transferred}\\ \text{to the object}\end{array}\right\} = \left\{\begin{array}{l}\text{force required to}\\ \text{lift the object}\end{array} \times \text{distance moved}\right\}$$

$$= mg \times h$$

So,

$$\begin{array}{l}\text{gravitational energy}\\ \text{of the object } E_{\mathrm{g}}\end{array} = mgh \qquad (13)$$

This equation says that the gravitational energy E_{g} of an object only depends on its weight mg and the height h to which it is lifted. This expression for the gravitational energy was derived assuming the principle of conservation of energy (as was our derivation of $E_{\mathrm{k}} = \frac{1}{2}mv^2$ in sub-Section 6.3).

When we say that an object has gravitational energy mgh, we mean that if it falls a distance h to the floor, the amount of energy mgh is converted into other forms. When it is on the floor it obviously cannot fall any further—it then has zero gravitational energy *with respect to the floor*. But suppose that the object, instead of being able to fall all the way to the floor, could only fall a distance d to the top of a table (see Figure 23). When it reached the table, it would have converted gravitational energy mgd to other forms of energy, and the object would then have zero gravitational energy *with respect to the table top*. Notice, though, that it would then still have gravitational energy $mg(h-d)$ *with respect to the floor*!

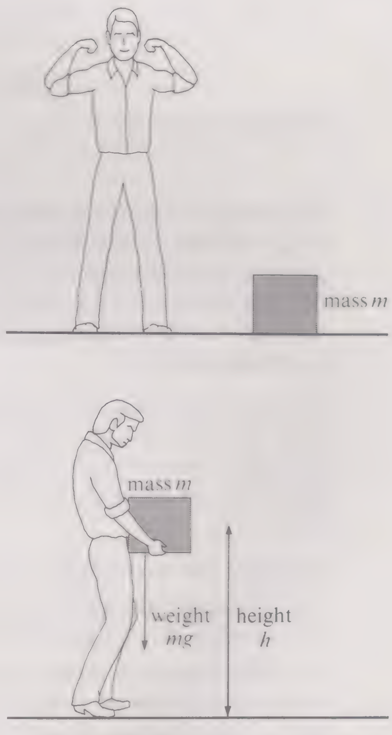


FIGURE 22 The energy transferred to the mass m in lifting it a height h against the force of gravity, is equal to the gravitational energy of the mass.

It doesn't matter where you specify the zero of gravitational energy to be (on the top of the table, on the floor, or even in between them)—all that matters is how far the object can fall, that is, how much energy it can transfer. When you say that an object has a certain gravitational energy, you should always say with respect to what point it has that energy. For example, the object in Figure 23 has gravitational energy mgh with respect to the floor and mgd with respect to the top of the table.

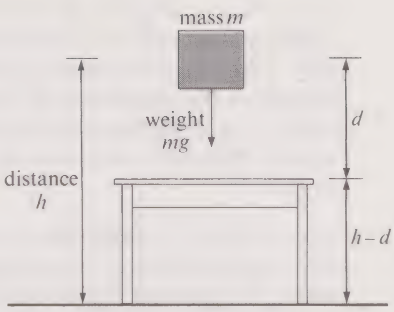


FIGURE 23 The mass m has gravitational energy mgh with respect to the floor, but it has gravitational energy mgd with respect to the top of the table.

You should now—in addition to applying the principle of conservation of energy and finding the energy transferred to an object by moving it a given distance by a constant force—be able to recall the simple expression for the gravitational energy of an object and be able to use this expression to solve simple problems concerning this form of energy. With these Objectives in view, try SAQs 10–12.

SAQ 10 Show that the dimensions of the product mgh are the dimensions of energy.

SAQ 11 Calculate how much muscular energy is required to lift a bag of potatoes which weighs 3 kg to waist height (3.5 feet above the ground). Check that your answer agrees with the appropriate entry in Table 2.

(The acceleration due to gravity is $9.8\,\mathrm{m\,s^{-2}}$ and $1\,\mathrm{ft} = 0.31\,\mathrm{m}$.)

SAQ 12 A slimmer, who weighs 10 stone (63.6 kg) polishes off some strawberries and cream in a restaurant near the bottom of the Post Office Tower in London and then consults a slimming guide which tells her that she has 'consumed 200 Calories'. Horrified, she decides to 'work off' some of this energy by walking up the 170 m flight of stairs in the Tower. Calculate how many Calories she 'walks off' in climbing the stairs once, assuming that the Calories are converted completely into muscular energy and that she converts this energy entirely to gravitational energy. Do you think that the second of these assumptions is reasonable?

(You will need to refer to Table 3 in sub-Section 4.3 and to note that the acceleration due to gravity is $9.8\,\mathrm{m\,s^{-2}}$.)

7.3 Conversion of gravitational energy into kinetic energy—the bouncing ball

If you lift a heavy object off the ground and then release it, it will accelerate downwards because of the gravitational force acting on it. As more of its gravitational energy is converted into kinetic energy, so it moves more quickly. Using the principle of conservation of energy, the speed of the object as it falls can be calculated quite easily.

Suppose that an object of mass m is lifted to height h above the ground and then allowed to fall. Use the principle of conservation of energy to find the speed at which it is moving when it hits the ground.

The principle of conservation of energy says that the total energy (gravitational + kinetic) of the ball is always the same. When it is at height h it has gravitational energy mgh with respect to the floor and no kinetic energy.

When the ball reaches the ground, all of the gravitational energy has been converted to kinetic energy, $\frac{1}{2}mv^2$ (where we have denoted the speed of object as it hit the floor as v).

$$\left\{\begin{matrix}\text{energy of ball as it}\\ \text{hits the floor}\end{matrix}\right\} = \left\{\begin{matrix}\text{energy of ball before}\\ \text{it is released}\end{matrix}\right\}$$

That is, $$\tfrac{1}{2}mv^2 = mgh$$

Dividing both sides by m and then multiplying both sides by 2:

$$v^2 = 2gh$$

Hence, $$\text{the speed } v = \sqrt{2gh} \tag{14}$$

The speed at which the object is moving, turns out not to depend at all on its mass: if a ten-ton lorry were to fall off the edge of a cliff, it would be moving no

faster when it reached the shore below than a pebble dropped from the same height. You shouldn't be surprised by this result, as you have already learned in Unit 3 that the gravitational acceleration of an object is independent of its mass because of the dependence of the gravitational force on the mass of the falling object. It is comforting to note, though, that the approach to the problem which uses the principle of conservation of energy gives the same result as we obtained in Unit 3.

Now try SAQ 13, which tests your understanding of equation 14. (It checks again that you can apply the principle of conservation of energy, and can recall and apply the equations for kinetic and gravitational energy.)

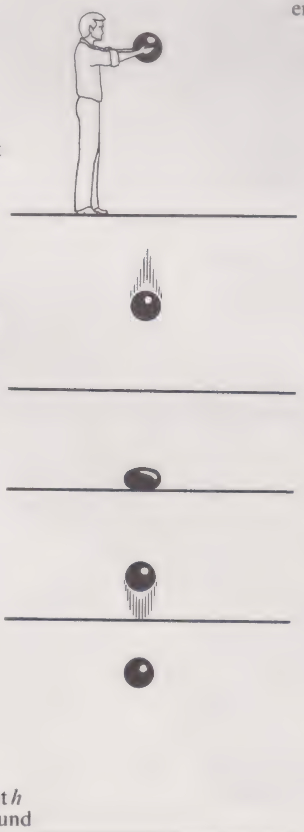
SAQ 13 A man walks up a flight of stairs and, when he is 20 m off the ground, he drops a suitcase over the banisters. How fast will it be moving when it hits the floor? If he had dropped it after he had walked up some more stairs, would the suitcase be moving any more quickly when it reached the floor? Give a reason for your answer.

Now suppose that the man were to drop a piece of paper over the banisters at the same time as he dropped the suitcase. Would you expect the two objects to reach the ground at the same time? If not, why not?

(The acceleration due to gravity $g = 9.8\,\mathrm{m\,s^{-2}}$.)

Now think about what happens when you drop a rubber ball—it falls to the ground, then bounces back up, falls again and so on. You probably know that the height to which it will bounce, gradually diminishes and that its motion gradually peters out.

For the moment though, consider the 'ideal' case in which the ball bounces right back up to the point from which it was dropped. Just before it is released (Figure 24a), it only has gravitational energy. When it is dropped, it accelerates downwards and, as it gets nearer to the floor, more of its gravitational energy is converted to kinetic energy (Figure 24b). When the ball is in contact with the floor it deforms (changes shape) and stores its energy as strain energy (Figure 24c). It then bounces back off the floor as its strain energy is converted back to kinetic energy (Figure 24d). Then the ball bounces back up to the same point from which it was dropped (Figure 24e). And so the motion goes on, with these energy conversions taking place during every bounce.



POSITION OF BALL		FORM OF ENERGY gravitational energy E_g	kinetic energy E_k	strain energy E_{st}
(a)	held at height h above the ground	mgh	0	0
(b)	half-way, $\frac{h}{2}$ to the ground	$\frac{mgh}{2}$	$\frac{mgh}{2}$	0
(c)	stationary on the ground	0	0	mgh
(d)	at height $\frac{h}{4}$ above the ground	$\frac{mgh}{4}$	$\frac{3mgh}{4}$	0
(e)	back to its original height h above the ground	mgh	0	0

FIGURE 24 The motion of an 'ideal' bouncing ball, which has different amounts of gravitational energy E_g, kinetic energy E_k and strain energy E_{st} when it is at different heights above the ground.

On Figure 24 we have stated the amount of gravitational energy E_g, kinetic energy E_k and strain energy E_{st} that the ball has at different stages. (There is no need at all to learn these amounts.)

ITQ 4 Use the values of E_g, E_k and E_{st} shown on Figure 24 to check that the total energy of the ball is conserved throughout its motion.

7.4 Energy graphs

There is a convenient way of showing the conversion of one form of energy to another, and that is by drawing graphs.

energy graphs

Consider the ball held at height h above the floor—it has gravitational energy mgh and, as long as it remains stationary, this is its total energy. After the ball has been released, its gravitational energy decreases uniformly from mgh to zero, at which point it hits the floor (Figure 25).

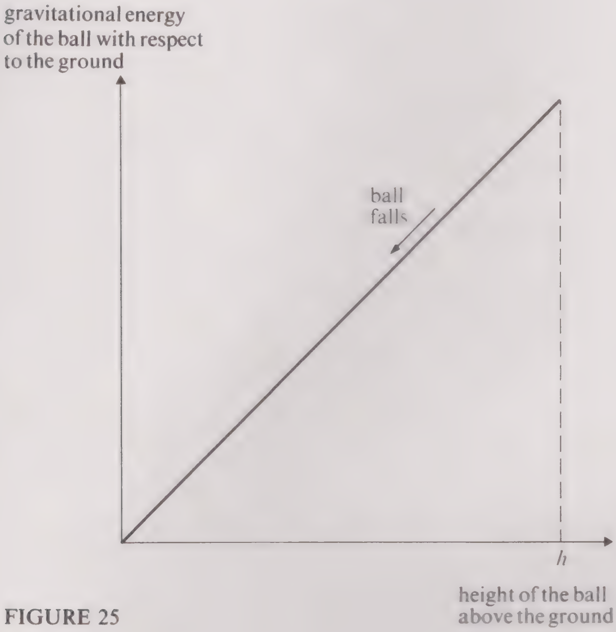


FIGURE 25

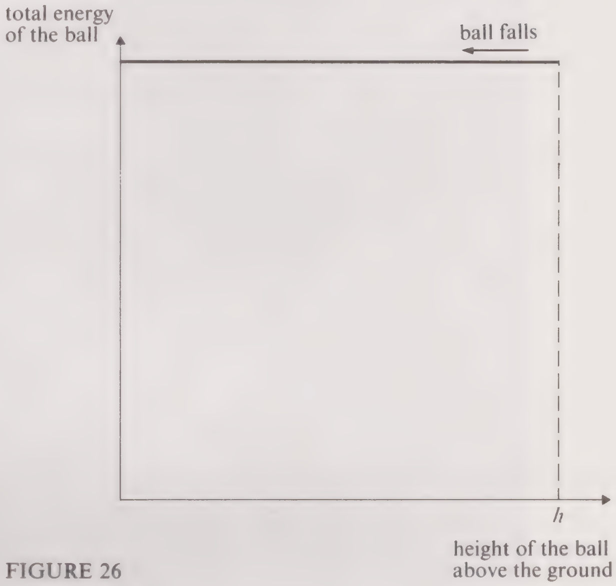


FIGURE 26

The principle of conservation of energy says that the total energy of the ball does not change (Figure 26). Hence, as the gravitational energy decreases during the fall, the kinetic energy of the ball must increase accordingly (Figure 27) until the ball hits the floor, at which point the total energy of the ball is equal to its kinetic energy. The graphs in Figures 25, 26 and 27 can all be superimposed (Figure 28).

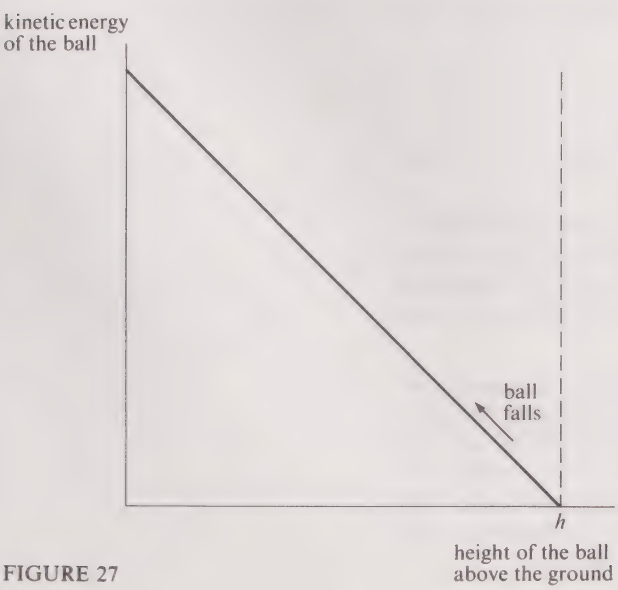


FIGURE 27

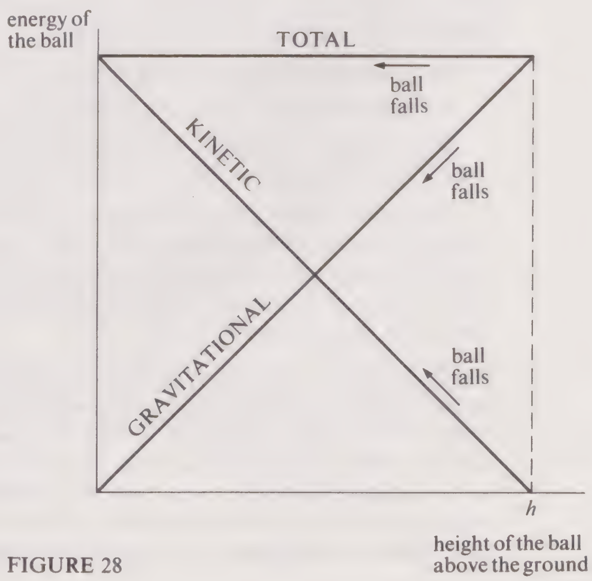
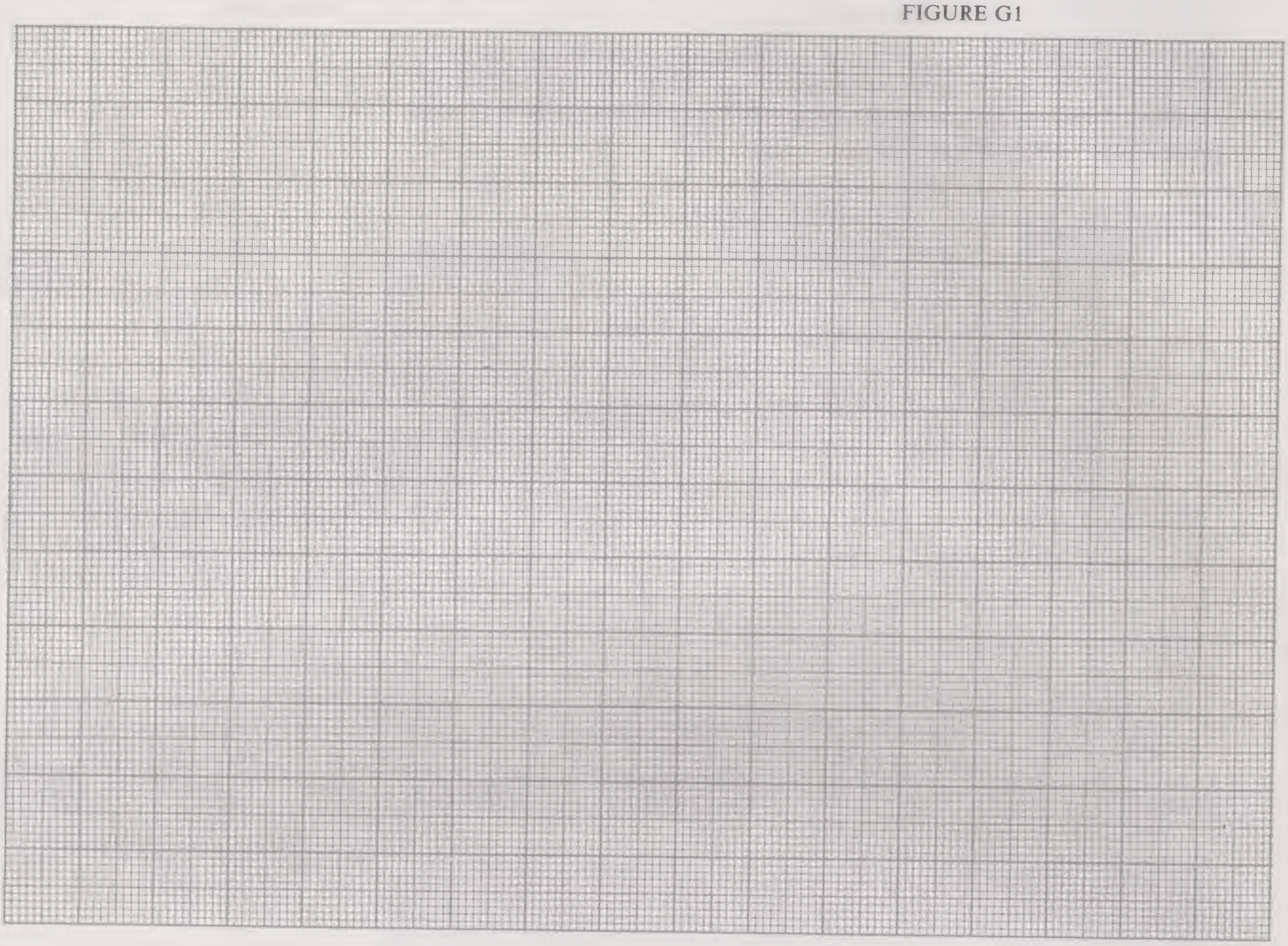


FIGURE 28

Having completed this sub-Section you should be able to sketch and interpret graphs that show the variation of kinetic energy, gravitational energy and total energy of a falling object. Try SAQ 14 to check your ability to do this.

SAQ 14 A pebble of mass 2×10^{-3} kg is dropped off the edge of a cliff, 100 m above the shore. Use the graph paper reproduced in Figure G1 to draw a graph that shows how the kinetic, gravitational and total energy of the pebble depend on its height above the ground. Use the graph to find how far the pebble is above the ground when it has the same amount of gravitational energy as of kinetic energy. Next, use the graph to find the height of the pebble off the ground when it is moving at $30\,\mathrm{m\,s^{-1}}$. (In this question, take the acceleration due to gravity g to be $10\,\mathrm{m\,s^{-2}}$.)

FIGURE G1



7.5 The story so far

This is a good place to pause for a moment and to note some of the main facts about energy that you have learned so far.

1 There are many different forms of energy.

2 The different forms can be converted into one another.

3 When energy is transformed from one form into another it is always conserved—energy can neither be created nor destroyed.

4 The energy transferred to an object by a *constant* force is simply the product of the force and the distance that it moves the object. Coupling this with the principle of conservation of energy, you saw that the kinetic energy of a moving body is $\frac{1}{2}mv^2$ and that the energy transferred to an object when it is moved distance h against the force of gravity is mgh.

In sub-Section 7.3, you saw how these facts can be used to study the motion of a bouncing ball. We indicated at the beginning of that sub-Section that the case in which the ball always bounces back up to the same height above the ground is the *ideal* case. What really happens when you drop a ball is that it bounces back, but *not* to the point from where you dropped it. The height that it reaches after every bounce decreases until its motion peters out and it eventually comes to rest on the floor. What has happened to its energy? We shall discuss this next.

7.6 More about the bouncing ball

If you can, find a tennis ball or any bouncy ball and see what happens when you drop it onto the floor from about waist height. You should find that it follows a path something like the one shown in Figure 29. In the Figure, the ball is dropped from A and it only reaches B after its first bounce. It has more gravitational energy with respect to the floor when it is at A than it has when it is at B. At first sight, it seems that some of the ball's gravitational energy has disappeared. How could the ball have lost some energy? Remember that the principle of conservation of energy says that energy cannot be destroyed, so some of the gravitational energy must have been converted into other forms of energy. Before you read on, note down some forms of energy into which you think the ball's energy might have been converted. (You may need to look back to Table 1 where we have listed some of the different forms of energy.)

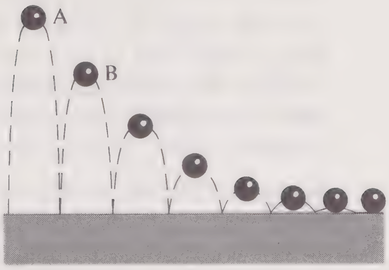


FIGURE 29 The motion of a 'real' bouncing ball—the height above the floor to which it bounces decreases with every bounce, until its motion eventually peters out.

A good way of keeping track of where the energy might have gone, is to follow the motion of the ball from A to B and to note the different forms of energy into which the ball's energy might be converted. First, as the ball falls through the air, the friction between the ball and the air causes the temperature of each to go up very slightly (so slightly that you couldn't hope to measure the increases with an ordinary thermometer), and we say that they gain *heat* energy: some of the energy of motion of the ball (its kinetic energy) is converted to heat energy of the ball and the atmosphere. The same process may also occur when the ball is coming up from the floor, after it has bounced. As it hits the ground, all of the ball's original gravitational energy has been converted into kinetic energy, so that it is moving very rapidly. Of course, the floor stops it from moving any further, so this kinetic energy must be converted into other forms of energy. But into which ones?

The thud that you hear when the ball hits the floor tells you that some of its kinetic energy is converted into *sound* energy. But that isn't all. When the ball hits the floor, the impact sets in motion the atoms in the floor and in the ball, transferring energy to them. As a result, both the ball and the floor get slightly warmer—they gain heat energy*. The increases in the temperature of the ball and the floor are very small indeed—far too small to be detectable with an ordinary thermometer.

There, then, are the ways in which we should expect the energy of the ball to be transferred and converted. As more of its energy is transformed, the height to which it bounces decreases, until its motion eventually peters out. The principle of conservation of energy actually enables you to tell *how much* of the ball's energy has been converted to other forms when the ball fails to return to its original height from the ground.

> If a ball of mass m is dropped from height h above the ground and it bounces back up to height s above the ground, how much of its energy must have been converted into other forms of energy?
>
> Initially, the ball has only gravitational energy mgh with respect to the floor. After the ball has bounced, it returns to height s at which point its gravitational energy is mgs, with respect to the floor. The principle of conservation of energy says that the energy of the ball cannot be destroyed but that it can be converted into other forms of energy such that the total energy is always conserved:
>
> $$\left\{\begin{array}{l}\text{initial gravitational}\\ \text{energy with respect}\\ \text{to the floor } (mgh)\end{array}\right\} = \left\{\begin{array}{l}\text{gravitational energy when ball is}\\ \text{at height } s\ (mgs) + \text{energy converted}\\ \text{to other forms (heat, sound, etc.)}\end{array}\right\}$$
>
> i.e. $mgh = mgs +$ energy converted to other forms. So the amount of energy converted to other forms is $mg(h - s)$.
>
> In other words, this equation says that if you were to measure all of the energy converted to other forms after one bounce, the amount that you would find is $mg(h - s)$.

In our account of the motion of the bouncing ball, you saw how the energy of the ball must be converted into other forms. We said that it is probably converted

* Don't worry if you don't understand clearly this connection between the heat energy of an object and the energy of its constituent atoms. We shall return to this subject in Section 9.

into two forms of energy: sound energy and heat energy. You can tell that some of the ball's energy is converted into sound energy as you *hear* it hit the floor. But you really had to take on trust our statement that some of the ball's energy would be converted into heat energy. A ball is certainly not warm to the touch after it has bounced a few times and the surrounding atmosphere does not become noticeably hotter when the ball has fallen through it.

In the next Section, we shall describe experiments in which kinetic and gravitational energy are converted into heat energy and in which the *amount* of heat energy into which they are converted is actually measured.

8 Heat energy

8.1 Introduction

James Joule was the owner of a brewery in Manchester and, at the same time, was one of the greatest physicists of the nineteenth century. When he was on his honeymoon, he found the time to do an experiment that was designed to show that gravitational energy could be converted into heat energy. Whether his wife approved of his experimentation is not recorded.

Joule tried to compare the temperature of the water at the top of a waterfall (point T in Figure 30) with that at the bottom (B), since he thought that the water would be warmer at the bottom.

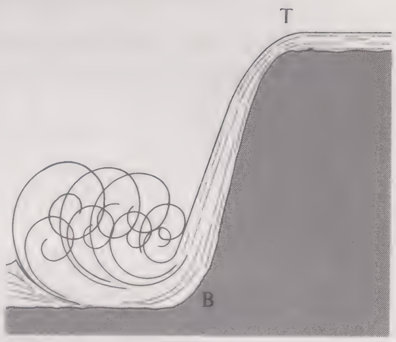


FIGURE 30 A waterfall.

Can you see why he thought this?

The water at the top has kinetic energy and it has gravitational energy with respect to the bottom of the waterfall. When it falls, its gravitational energy is converted into kinetic energy.

The water is prevented from falling any further when it reaches B and the speed of its flow is reduced, so that its kinetic energy is also reduced. Some of the kinetic energy that it has when it reaches B will be converted to another form of energy. If this form is heat energy, the water will be hotter at the bottom than it is at the top.

This experiment is reminiscent of the one with the bouncing ball that we described in the last Section. There, some of the kinetic energy of the ball is converted to other forms of energy but, in the case of the waterfall, it is some of the kinetic energy of the *water* that is converted.

Unfortunately, Joule was unable to detect any difference between the water's temperature at the bottom and at the top. It would have been remarkable if he had done, as later calculations showed that it would only be about 10^{-2} °C. To find out how much heat energy can be converted from a supply of gravitational energy, Joule did some extremely precise experiments with various pieces of apparatus that he designed and built over a period of seven years (1843–50). In the next sub-Section, we shall describe one of these pieces of apparatus.

8.2 Joule's apparatus

The method that Joule used to study the conversion of gravitational energy into heat energy, involved the vigorous stirring of liquids. He designed pieces of apparatus in which the gravitational energy of a weight is transferred to a stirrer that, in turn, acquires kinetic energy that is then transferred to a liquid. His aim was to measure the rise in temperature of the liquid after energy had been transferred to it.

Joule's apparatus

Look at Figure 31, which is a sketch of one of the pieces of apparatus that Joule used. It consists of a container of water in which is mounted a stirrer which is driven by the falling of a weight. When the weight falls, the stirrer turns (it acquires kinetic energy) and then transfers its energy to the water. To prevent the

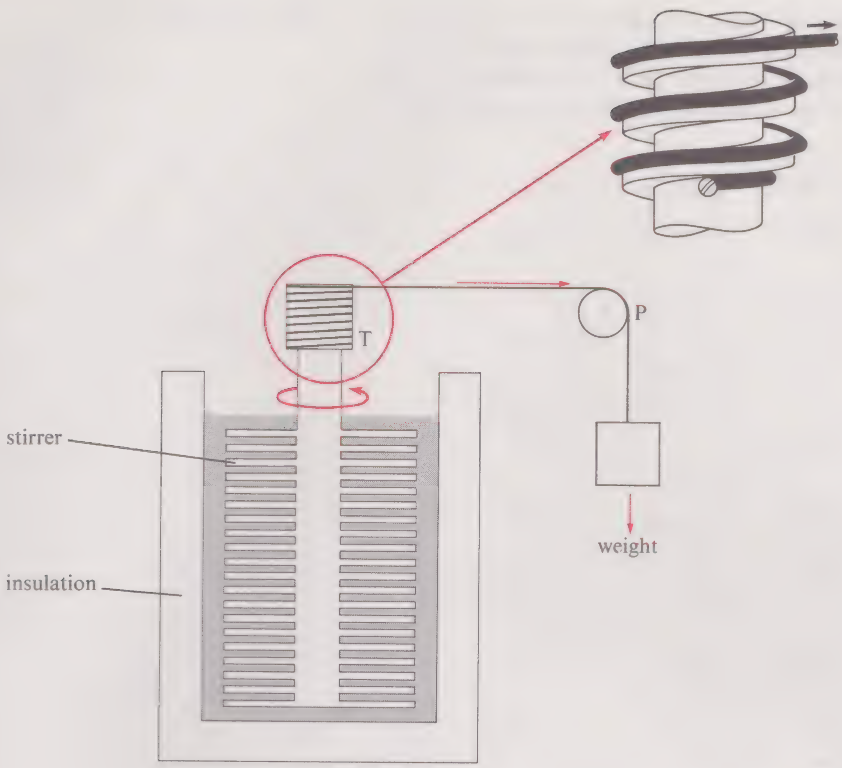


FIGURE 31 Joule's apparatus.

heat energy from 'leaking' away to the surrounding atmosphere, the container is thermally insulated (lagged).

There is some friction between the string and the pulley and the screw thread (P and T on Figure 31): this will mean that a *tiny* amount of the weight's gravitational energy will be converted to heat energy at these points. Also, the string makes a noise as it moves over the pulley, so some of the weight's gravitational energy must also be converted to sound energy. (In practice this loss is very small.)

The principle of conservation of energy says that the energy of the system before the weight falls is equal to the energy of the system *after* it has fallen. By assuming that *all* of the kinetic energy of the stirrer is transferred to the kinetic energy of the water in the container and that, when the motion of the water ceases, all of its kinetic energy is converted to heat energy, Joule could then calculate the total amount of energy transferred to the water. For example, suppose that before the weight falls, its gravitational energy with respect to the floor is 20 J and that its kinetic energy when it hits the floor is 1 J, then the energy transferred to the water (its heat energy) will be 19 J, neglecting the losses of heat and sound energy that we mentioned before.

The question is, how much does the temperature of the water go up after this energy has been transferred to it? Joule found that *as more energy was transferred to the water, so its temperature increased.* This is consistent with the intuitive idea that a liquid should have more energy when it is hot than when it is cold.

But note that to measure the temperature increase of the water is not directly to measure its increase in heat energy. We shall explain why in the next sub-Section.

8.3 The difference between heat energy and temperature

The concept of temperature is a familiar one—it means the 'degree of hotness' of something. Ice and boiling water feel different to the touch, and one of the ways in which we describe this difference is by saying that they have different temperatures. We say that when water freezes and forms ice its temperature is 0 °C ('zero degrees Celsius or centigrade') and that when it boils and forms steam, its temperature is 100 °C. In this way, thermometers are calibrated—they are made so that they read 0 °C when immersed in ice, and 100 °C when immersed in boiling water.

boiling temperature

A thermometer scale is shown in Figure 32 where, in addition to 0 °C and 100 °C, we have also marked the temperature of the blood in the human body (36.9 °C) and the approximate temperature of the atmosphere on a hot summer's day in Britain. Note that the temperature is not always measured in degrees Celsius.

temperature scales

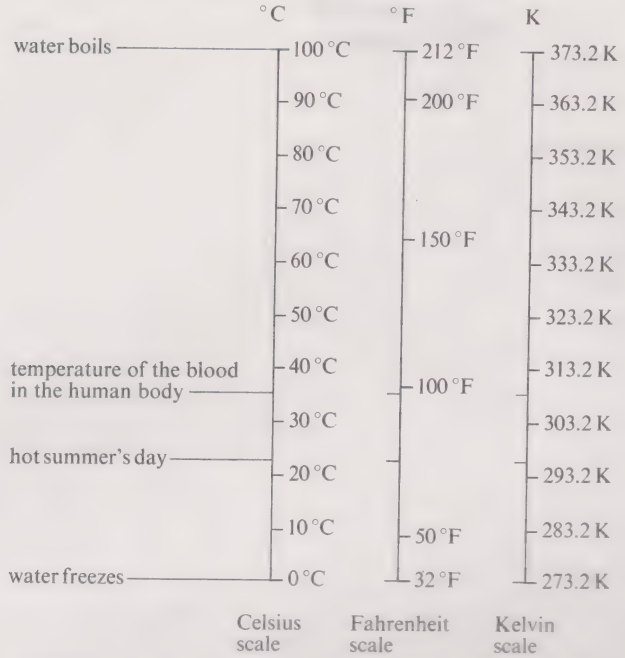


FIGURE 32 The Celsius, Fahrenheit and Kelvin scales of temperature.

Sometimes you will hear temperatures quoted in degrees Fahrenheit and in kelvin*. In recipes for cooking, oven temperatures are often quoted in both degrees Fahrenheit and degrees Celsius. On the Fahrenheit scale, water freezes at 32 °F and boils at 212 °F (see Figure 22). Needless to say, it makes no difference which scale you use.

In science, temperature is usually quoted in kelvin (the SI unit); on this scale, water freezes at 273.2 K and it boils at 373.2 K (Figure 32). The reason why this scale is used is because the temperatures 0 K is theoretically the lowest temperature which any object can approach—it is the so-called 'absolute zero'. No one has ever measured a temperature equal to or less than 0 K, but in some experiments this temperature is approached to within 10^{-6}K.

Are heat energy and temperature the same thing?

To answer this, imagine that you wanted to boil some water. You would probably not use the same method to transfer energy as was used in Joule's experiment (stirring)—if you did use that method it would take a very long time to warm the water (as you will see when you have answered SAQ 17). You would be more likely to use electrical energy from the mains or chemical energy from a supply of gas (Figure 33).

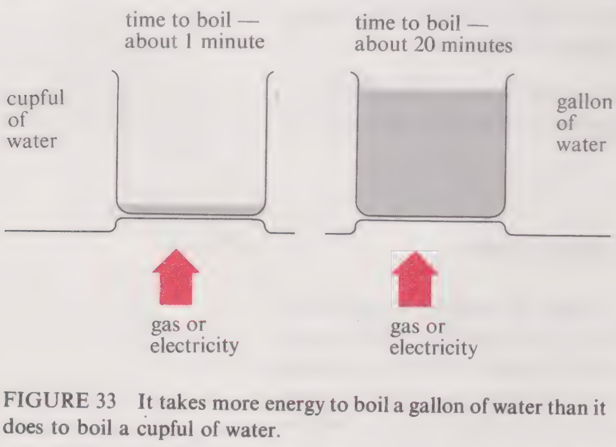


FIGURE 33 It takes more energy to boil a gallon of water than it does to boil a cupful of water.

* Note that in this scale, we do not refer to degrees Kelvin, but to just kelvin.

Each of these sources supplies energy at a constant rate, and it is clear that boiling a cupful of water takes less time than boiling a gallon. The conclusion is that the cupful of boiling water has *less* heat energy than a gallon of boiling water, *even though they are at the same temperature*. This serves to show that heat energy and temperature are not the same thing. But now another question arises.

How are heat energy and temperature *related*?

Suppose that the saucepans shown in Figure 33 were filled with the *same* amounts of water. You know that it takes more energy from the supply to heat one, by, say, 80°C than it would to heat the other by, say, 20°C from the same starting temperature. The higher the temperature to which an object is warmed, the more energy must be transferred to it, that is the more heat energy it has. In fact, experiments show that the temperature increase of a given substance is directly proportional to the energy supplied—its temperature increase is directly proportional to its increase in heat energy.

8.4 More about Joule's experiment

You have just seen that the energy transferred to the water, which is equal to the increase in its heat energy E_h, is directly proportional to its temperature rise ΔT:

heat energy E_h

$$E_h \propto \Delta T \tag{15}$$

Joule also found that if the *mass* of the water is doubled, then double the amount of energy must be transferred to raise its temperature by the same amount: the increase in the heat energy E_h of the water is directly proportional to its mass m:

$$E_h \propto m \tag{16}$$

This is what you'd expect from the example in the last sub-Section, where we pointed out that it takes much less energy to heat a cupful of water from room temperature to boiling temperature than it does to heat a gallon (a much larger mass of water).

So far, you have seen that the heat energy of the water depends on two factors: its mass and the increase in its temperature. But what if, *instead* of water, another liquid were used in the container? If you supplied a certain amount of energy to the *same* masses of water and some other liquid, would you expect that their temperatures would increase by the same amounts? There is no reason to suppose that they would—in fact, the heat energy of an object depends on the material from which it is made.

The heat energy required to increase the temperature of an object depends on three factors:

(i) its mass, m (see equation 16);

(ii) its increase in temperature, ΔT (see equation 15);

(iii) the material from which it is made.

Equations 15 and 16 can be combined into one:

$$E_h \propto m\Delta T \tag{17}$$

According the statement (iii), the constant of proportionality is different for each substance: it is known as the 'specific heat' of the substance and it is denoted by the letter c.

specific heat c

$$E_h = mc\Delta T \tag{18}$$

Equation 18 is quite general—it tells you how much energy has been transferred to an object in raising its temperature by a certain amount, provided you know the object's mass and specific heat. You could, for example, use it to find how much energy has been transferred to the bouncing ball of Section 7, provided you knew the ball's mass, specific heat and its increase in temperature after its bounce. You would have to measure its mass and the increase in its temperature and you could look up its specific heat in a Table like Table 5.

Given equation 18 for the heat energy of a substance, find the units of specific heat.

The units of heat energy E_h are joules, the units of ΔT are the units of temperature, °C (degrees Celsius), and the units of specific heat c are required. The units of both sides of the equation must be the same:

$$J = kg \times (\text{units of } c) \times {}^{\circ}C$$

so that the units of specific heat c are $J\,kg^{-1}\,{}^{\circ}C^{-1}$.

TABLE 5 The specific heat of some common substances

Substance	Specific heat $J\,kg^{-1}\,{}^{\circ}C^{-1}$
water	4.2×10^3
paraffin	2.1×10^3
air	9.9×10^2
aluminium	9.1×10^2
copper	3.4×10^2
iron	1.1×10^2

We give the specific heats of some common substances in Table 5, from which you can see how large is the specific heat of water compared with that of other substances. Notice also that the specific heat of copper is less than half that of aluminium.

In that case, would it take more or less energy to warm a piece of copper of a given mass through 1 °C as it would to warm a piece of aluminium of the *same* mass, through the same temperature?

The energy required = mass × specific heat × temperature change.

If the mass of the copper is m kg and its specific heat is, say, $c_1\,J\,kg^{-1}\,{}^{\circ}C^{-1}$, the energy required to warm it through 1 °C is mc_1 J.

If the specific heat of aluminium is denoted $c_2\,J\,kg^{-1}\,{}^{\circ}C^{-1}$, then the energy required to warm through 1 °C is mc_2 J.

For the *same* masses of copper and aluminium, the energy required will be proportional to the specific heat. The specific heat of copper is *less* than that of aluminium (see Table 5) so that it takes *less energy to warm the mass of copper*. This means, for example, that a copper saucepan would take a shorter time to warm up to a given temperature than an aluminium one of the same mass, provided that the same amount of energy were used to do the warming.

That concludes our discussion of heat energy. You should now be able to:

(a) Recall that the heat energy of an object depends on its mass, its specific heat and on the temperature through which it is heated.

(b) Do simple calculations to determine the amount of heat energy required to heat a substance from one temperature to another.

To check that you have achieved these Objectives try SAQs 15–17.

SAQ 15 Someone does experiments with two different sets of Joule's apparatus—one in which water was used in the container, the other in which paraffin was used. If, in each case, 20 J of energy were transferred to the liquids and there were 0.1 kg of the liquids in the container, how much greater would be the rise in the temperature of the paraffin compared with that of the water?

(Use Table 5 to find the specific heats of the two substances.)

SAQ 16 What facts would you need to know if you wanted to find the amount of energy required to boil a saucepan of milk?

SAQ 17 Someone runs a bath of water and finds that it is too cold to get into. To warm it up, the person follows Joule's example by stirring it vigorously with a loofah.

Suppose that the person stirs 100 times with a constant force of 0.4 N over a distance of 1 m *each* time and that the mass of the bath-water is 100 kg. Calculate the increase in the temperature of the bath-water caused by the stirring, assuming that all of the stirrer's muscular energy is converted to heat energy of the bath-water.

What approximations are being made in this calculation?

(Take the specific heat of bath-water to be that of water, see Table 5.)

9 A closer look at heat energy and temperature

9.1 Heat energy, temperature and atoms

For a better understanding of heat energy and temperature, it is necessary to have some knowledge of the structure of the matter from which these objects are made. You will be learning more about this later but, for the moment, all you need to know are a few of the basic ideas.

One of the most important discoveries of modern science is that all types of matter—solids, liquids and gases—are made of tiny particles which are called 'atoms'. These particles are far too small to be seen with the naked eye or even with the most powerful optical microscopes. There are many different types of atom and they can be bound together in many different ways: this is why matter comes in so many forms.

The atoms in a substance are always in motion. To see this, you might like to do a simple experiment—*gently* drop a small blob of ink on to the surface of a *still* glass of water. If you leave the glass and its contents for an hour or so, you will find that the ink has spread out uniformly through the water—this is called diffusion. Although the blob of ink as a whole has no energy of motion, each of the atoms within it has kinetic energy. Each atom is free to move through the boundary between the ink and the water, until the two liquids are inextricably mixed. Solids and gases also consist of atoms that are in motion, although we shall not ask you to do Home Experiments to show this.

diffusion

The higher the temperature of a substance, the greater the average kinetic energy of its constituent atoms: the heat energy of the substance is a measure of the total amount of kinetic energy of these atoms. If you transfer energy to an object, this energy is shared among the individual atoms, and the heat energy and temperature of the object increases.

You may have wondered why we related the temperature of a substance to the *average* kinetic energy of its constituent atoms. This is because the atoms in the substance do not all move at the same speed. The graph in Figure 34 shows the numbers of atoms moving at different speeds in a *gas*: a graph like this one is known as a 'Maxwell–Boltzmann distribution' named after James Clerk Maxwell and Ludwig Boltzmann who, near the end of the nineteenth century, formulated a theory which predicted the shape of the graph. This prediction was later verified by experiments. Note that we have not stated the speeds at which the atoms move and the exact numbers of the atoms which move at these speeds. All that we are interested in here, is the way in which the number varies with speed.

Maxwell–Boltzmann distribution

FIGURE 34 The Maxwell–Boltzmann distribution of the speeds of the atoms in a gas.

Since the temperature of a gas is related to the average kinetic energy of its constituent atoms, how will the distribution (graph) shown in Figure 34 change when the temperature of the gas that it describes goes up?

If the temperature of the gas increases, the average kinetic energy of its constituent atoms will also increase and so, therefore, will their average speed. This is because the kinetic energy E_k and speed v of an atom are related: $E_k = \frac{1}{2}mv^2$, where m is the atom's mass. The shape of the distribution will alter in the way shown in Figure 35. You can see now that a greater number of atoms in graph (b) have higher speeds than those in graph (a). This means that the *average speed* calculated for *all* the atoms in the gas will be higher in (b) than in (a).

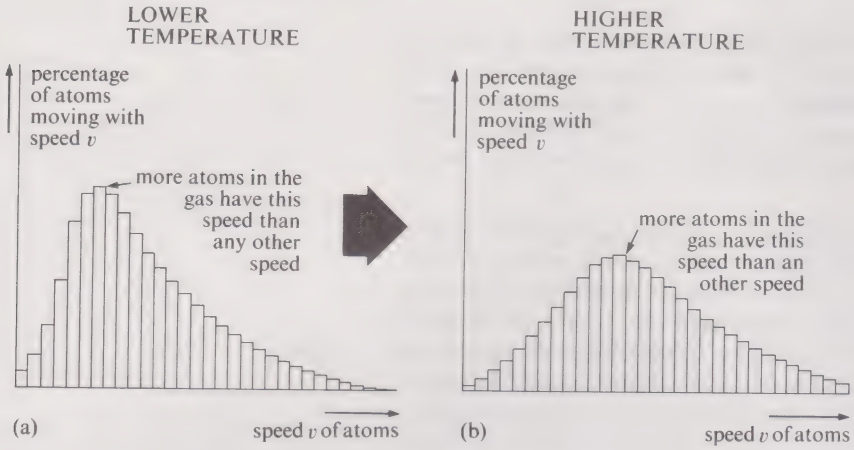


FIGURE 35 The change of shape of the Maxwell–Boltzmann distribution as the temperature of the gas increases.

One important point is that the motion of atoms in material objects is not ordered or regular—their motion is *entirely random*. For this reason, the heat energy of an object may be called the kinetic energy of the random motion of its constituent atoms.

9.2 Solids, liquids and gases

The description of matter as being made of tiny particles (atoms) can explain why there are three types of matter: solids, liquids and gases. To understand this, the only refinement that needs to be made to the simple picture of substances being composed of moving atoms is to introduce the forces that exist between the atoms.

In solids, the forces between the atoms are such that the atoms are bound in fixed positions about which they vibrate in random directions. Because the atoms in solids are not free to move about, solids are fairly rigid. The reason why all solids are not of the same rigidity is because they are made of different atoms and there are different forces between them. Figure 36 is an illustration of a few atoms' vibrating in a solid—we concentrate on only very few atoms for the purposes of

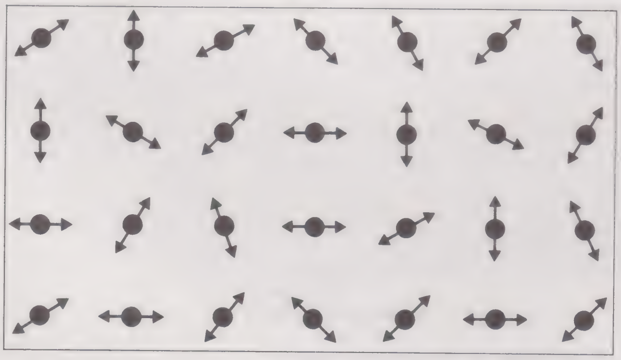


FIGURE 36 Atoms vibrating randomly about fixed positions in a solid.

illustration. The arrow 'attached' to each of the atoms indicates the direction in which it is vibrating at a particular instant. The arrows point in different directions to indicate that the direction of vibration is *random*, and will be quite different at some other instant.

As the temperature of the solid is raised, the average kinetic energy of the atoms increases and so they vibrate more vigorously. At the temperature at which the solid melts (its 'melting point'), the vibrations are so vigorous that they overcome the forces that bind the solid in its rigid shape and the solid turns into a liquid. In the liquid, the atoms not only vibrate, they also wander around quite freely (Figure 37). Again, as the temperature is increased still further, the average kinetic energy of the atoms increases and they move more and more quickly. When the liquid boils, the atoms have sufficient energy to escape from the forces which bind them to their neighbours and a gas is formed. The atoms now travel around freely and they frequently collide and exchange kinetic energy (Figure 38). If the temperature is increased further, the atoms, on average, travel faster still.

melting temperature

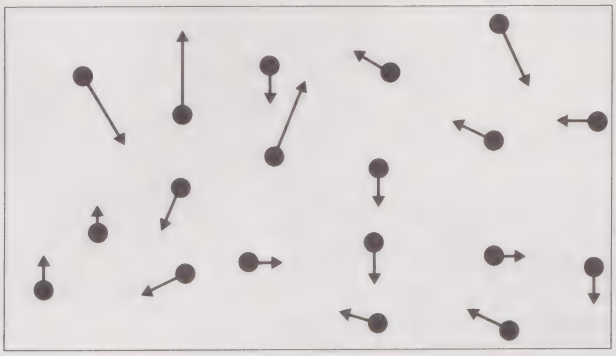


FIGURE 37 Atoms moving randomly around in a liquid.

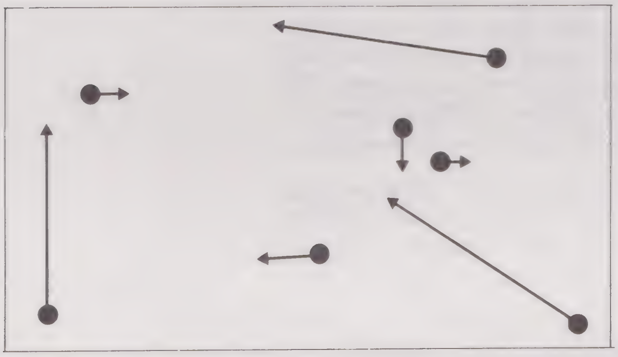


FIGURE 38 Atoms moving around randomly and independently in a gas.

Now that you have completed Section 9 you should be able to:

(a) Recall what happens to the average kinetic energy of the atoms in a substance when its temperature changes. (SAQ 18)

(b) Recall the form of the Maxwell–Boltzmann distribution of the speeds (or kinetic energies) of the atoms in a gas. (SAQ 18)

(c) Relate the three states of matter to the dependence of the average kinetic energy of the constituent atoms on temperature. (SAQ 19)

To check that you have achieved these Objectives, try SAQs 18 and 19.

SAQ 18 When a red-hot poker is plunged into cold water, the water warms up and some of it boils off as steam. Describe what happens to the atoms in the poker and to the atoms in the water.

Sketch the distribution of the speeds of the atoms in the steam.

SAQ 19 Consider the following statements and for each say whether it is true or false and give a reason for your answer.

(a) The average kinetic energy of the atoms in a gas whose temperature is 22 °C is less than that of the same gas when its temperature is 30 °C.

(b) The force between two atoms in a solid is always much less than the force between two atoms in the liquid formed after the solid has melted (assuming the separation between the two atoms is the same in both cases).

(c) When the temperature of a gas increases, the kinetic energy of each of its constituent atoms increases.

10 Electrical energy

10.1 Introduction

In this Section, we shall be discussing electrical energy, the last form of energy that we shall consider in detail.

We begin in sub-Section 10.2 by discussing the forces between charges and then, in sub-Section 10.3, we go on to consider the energy transferred by moving charges, that is by an electric current.

10.2 Forces between charges

The mains electricity supply is not the only source of electrical energy—it can also be obtained from batteries. These come in different sizes—a small one is usually sufficient to run something like a torch bulb or a pocket calculator, but a much larger one is needed to run the electrical components in a car. Each battery is labelled according to its voltage and we shall explain the meaning of this term later.

You saw in the TV programme associated with Unit 5 (TV05) that when a battery is connected to an electrical device something *flows* in the connecting wires, and we said in Section 5.1 of Unit 5 that what actually flows are 'tiny particles called electrons, . . . which have a property called charge'. In fact, it is *this flow of charge that is responsible for the electrical energy transferred to the device.* The charge is made available within the battery by the reaction of different chemicals: the battery is simply a device that converts chemical energy into electrical energy.

You are probably wondering what charge is. How can you tell whether an object is charged? Can you actually see charge flow? We shall answer these questions later but, for the moment, we shall point to some examples where you can see the *effects* that charge can have when it is *not* flowing in the wires of electrical devices, that is, when it is static.

A gramophone record tends to attract dust from the atmosphere: there is a force between them. Also, if you have ever taken off a nylon jumper from over a shirt or blouse (particularly on a dry day), you may have noticed that they tend to attract each other—they have acquired charge and again there is a force between them. When taking the jumper off, you may even hear crackles and, if you are in a darkened room, you may see sparks fly. This only happens when garments are charged; normally, they are uncharged and they don't crackle and give off sparks when they are near other garments.

In everyday life, you probably do not come across many charged objects, yet charged is an extremely important concept in science, as you will see in this Course.

Many experiments have been done to find out about the properties that charged objects have, and to find out what carries the charge. Regrettably, there is not enough time to discuss these experiments in detail. We hope that, for the time being at least, you will accept on trust the following summary of experimental results:

1 Any object can have one of two types of charge or it can have none at all. The two types of charge are normally called 'positive charge' and 'negative charge'.

positive and negative charge

2 When something is charged, it does not appear any different—you cannot see or hear the presence of charge and it has no shape or size. (A nylon jumper doesn't look any different if it is charged.) The only way in which you can tell that something is charged is to see whether it will interact with another charged object.

The question is, what laws describe their interaction?

3 If two stationary objects are brought together and they *both* are positively charged or *both* are negatively charged, then they always repel each other (see Figure 39). The force that pushes them apart is described as 'electrostatic'.

electrostatic force F_{el}

4 If two stationary objects have *opposite* charge (one positively charged, the other negatively charged), then they always attract. The force that pulls them

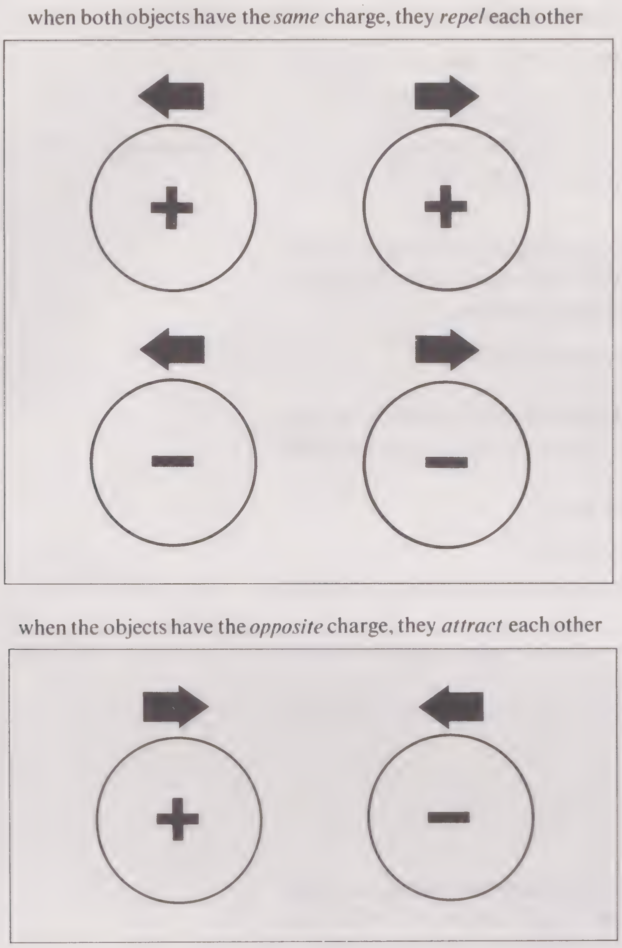


FIGURE 39 The interactions of charged, point-like particles.

together is also known as electrostatic (see Figure 39). Notice that the electrostatic force can either be attractive or repulsive, according to whether it acts between like or unlike charges. It is, therefore, different from the gravitational force, which is *always* attractive. Another point worth noting is that the gravitational force between two charged objects is always very much smaller than the electrostatic force between them.

5 The magnitude of the electrostatic force F_{el} between two stationary charged objects depends on the inverse square of the distance between them and on the product of the magnitude of the charges Q_1 and Q_2, on the objects:

$$F_{el} \propto \frac{1}{r^2}; \qquad F_{el} \propto Q_1 Q_2$$

i.e.

$$F_{el} \propto \frac{Q_1 Q_2}{r^2} \tag{19}$$

This is known as Coulomb's law and, strictly speaking it applies only to extremely small (point-like) objects. The units in which the charge Q is measured are coulombs, usually abbreviated to C.

Coulomb's law

coulomb C

Equation 19 can also be written as:

$$F_{el} = \frac{AQ_1 Q_2}{r^2}$$

where A is the constant of proportionality, which is determined by experiment. It turns out that the value of A is $9 \times 10^9\,\mathrm{N\,m^2\,C^{-2}}$.

Coulomb's law says that there is no electrostatic force between two objects if either or both of them are uncharged: if $Q_1 = 0$ or $Q_2 = 0$, or if both Q_1 and $Q_2 = 0$ then $F_{el} = 0$. However, the gravitational attraction between the objects persists, as it does even if there *are* electrostatic forces between them.

6 In stating the above results 3–5, which concern electro*statics*, we were careful to point out that they apply to *stationary* charges.

What force acts between charges when they are moving?

As you saw in Unit 5, there is a force between two currents, that is between the *moving* charges in the wires—we said that this force is called the 'magnetic force'. Sometimes the electrostatic and magnetic forces are collectively referred to as electromagnetic forces. Thus, it is said that the force between charged particles is electromagnetic as this avoids the need to specify whether the particles are moving*.

electromagnetic force

Now that you have completed this sub-Section you should be able to recall the properties of charge that we have given and be able to use Coulomb's law to find the electrostatic force between two stationary charged particles.

To test that you have achieved these Objectives, try SAQ 20.

SAQ 20 Picture four stationary tiny dust particles, which we label as A, B, C and D for convenience. A is uncharged, B is positively charged and both C and D are negatively charged.

(a) What are the forces acting between B and C?

(b) What are the forces acting between C and D?

(c) What is the magnitude of the electrostatic force between A and C when they are separated by 2 m?

(d) Suppose that the magnitude of the electrostatic force between B and D is 1.15×10^{-28} N when they are separated by 2 m. What is the magnitude of the electrostatic force between them when they are separated by 4 m?

10.3 The flow of charge—electric current

In Section 7, you saw that, because there is a gravitational force between an object and the Earth, any object has gravitational energy which can be converted into other forms of energy if it falls. Similarly, if two charges are separated there is force between them: separated charges have *electrical* energy and they can transfer this energy when they move.

If the terminals of a battery are connected by copper wires, an electric current flows. We said in Unit 5 (though we did not prove it) that negatively charged particles called electrons flow through the wires from the negative terminal to the positive terminal. One way to explain why this happens is to say that the electrons are repelled by the negative terminal and are attracted by the positive terminal. Alternatively, we can use an energy argument, and say that the charges flow to the positive terminal because their electrical energy is lower at that terminal. This is analogous to saying that a body will fall to the Earth when released, because its gravitational energy is thereby reduced.

The difference in the electrical energy of a charge at two positions is determined by the difference in *voltage* between those positions. The voltage difference can be defined as the electrical energy difference per unit of charge, and this is commonly abbreviated to potential difference. We can write this definition in the form of an equation:

$$\text{voltage difference } V = \frac{\text{electrical energy difference } E_{\text{el}}}{\text{charge } Q}$$

electrical energy E_{el}

or

$$V = \frac{E_{\text{el}}}{Q} \tag{20}$$

This can be rearranged, to express the energy difference in terms and the charge:

$$E_{\text{el}} = QV \tag{21}$$

The common unit of voltage difference is the volt, which is defined such that the voltage difference between two places is exactly one volt if the transfer of one

volt V

* If only one of the charged particles is in motion, the force between them is still electrostatic.

coulomb of charge between the two places requires an energy transfer of one joule. Thus:

$$1 \text{ volt} = 1 \text{ joule per coulomb}$$
$$= 1\,\text{J}\,\text{C}^{-1}$$

Let us illustrate the use of this definition with a simple example. If 250 coulombs of charge are transferred from the negative terminal of a 12-volt car battery via the starter motor to the positive terminal, then the decrease in electrical energy of the electrons involved is:

$$E_{el} = 250 \text{ coulombs} \times 12 \text{ volts} = 3\,000 \text{ joules}$$

This amount of electrical energy is converted into energy of motion (kinetic energy) of the starter motor and engine, and into heat energy.

ITQ 5 Given that the magnitude of the charge on the electron is 1.6×10^{-19} C, calculate the energy (in units of joules) that must be transferred to an electron if it is to be moved between two places which have a voltage difference of 1 V. (This amount of energy is known as the electronvolt eV, which we first mentioned in sub-Section 4.3. You might care to check that your answer to this question agrees with the appropriate entry in Table 3 of that sub-Section.)

When we discuss the operation of an electrical device, we don't usually discuss how much charge flows through it in a given time, rather we discuss the *rate* at which charge flows through it. This rate is so important that it is given a name, current (usually denoted by the letter I).

i.e. $$I = \frac{\text{amount of charge } Q \text{ flowing between two points}}{\text{time } t \text{ taken for the charge to flow}} = \frac{Q}{t} \qquad (22)$$

The unit of current is that of charge (coulomb) divided by that of time (second): $\text{C}\,\text{s}^{-1}$. This unit is also given a special name, the ampere, usually shortened to the amp, A.

amp A

The electricity board supplies homes with charge; all that consumers have to do is to plug their gadgets into the mains supply and the charge flows down the connecting wires, making electrical energy available for conversion into other forms. The voltage of a consumer's mains supply is always the same but different devices require charge to be delivered at different rates in order to operate them. The rates at which these devices convert electrical energy is usually marked on them: you saw in Section 4 that the rate of converting energy is usually called power. Do you remember the units of this quantity?

Power is measured in joules per second, that is, watts, often abbreviated to just *W*. A typical power-rating for an electric fire is 2 kW = 2 000 W. This means that it converts 2 000 joules of electrical energy to other forms of energy (mainly heat) in one second. Compare this with a 60 W electric light bulb, which converts 60 joules of electrical energy per second into other forms of energy (mainly heat but also a little light).

ITQ 6 An electrical device is connected to a supply of electricity rated at V volts and a current of I amps flows in the circuit for t seconds. Use equations 21 and 22 to calculate the power-rating of the device.

You might care to look at some of the items of electrical equipment in your home (like the TV, radio, cooker, etc.) and compare the rate at which they convert their supply of electrical energy to other forms. When you are using these pieces of household equipment, you should bear in mind that they are really just devices designed to convert the energy of the charges flowing into them into forms of energy that can be used to do useful jobs.

Now that you have finished this sub-Section you should be able to recall equations 21 and 22 and apply them to simple problems on the flow of current. Try SAQs 21–23.

SAQ 21 Suppose that 100 J of electrical energy are converted completely into heat energy when a certain amount of charge flows from the negative terminal to the positive terminal of a 1.5 V torch battery. How much charge flowed?

SAQ 22 A current of 0.2 A flows for 1 minute in the wires connecting a torch bulb to its battery. How much charge flowed in that time?

SAQ 23 A constant current of 40 A flows in the wires that connect a 12-V car battery to the car's starter motor. Calculate the electrical energy transferred to the motor in 5 s.

11 An energy crisis?

We have now finished our discussion of the various forms of energy and the ways in which they can be converted into one another. The all-important principle that governs such energy transformations is the principle of conservation of energy, which says that the total amount of energy in a physical system is always conserved—energy can neither be created nor destroyed. Since energy cannot be destroyed, you may well ask why there is so much talk of an energy crisis, by which is meant that there is some threat of running out of energy to heat our homes, to run our cars and to operate our industries. After all, if the energy in the world cannot be destroyed, why should we worry about how much we use? This question is a good and pertinent one, and we shall answer it in this Section.

The first question that we need to answer is: what happens to the energy we 'use'? Take as an example the sequence of energy transformations illustrated in Figure 40. You can see that a major portion of the energy that goes into a power station

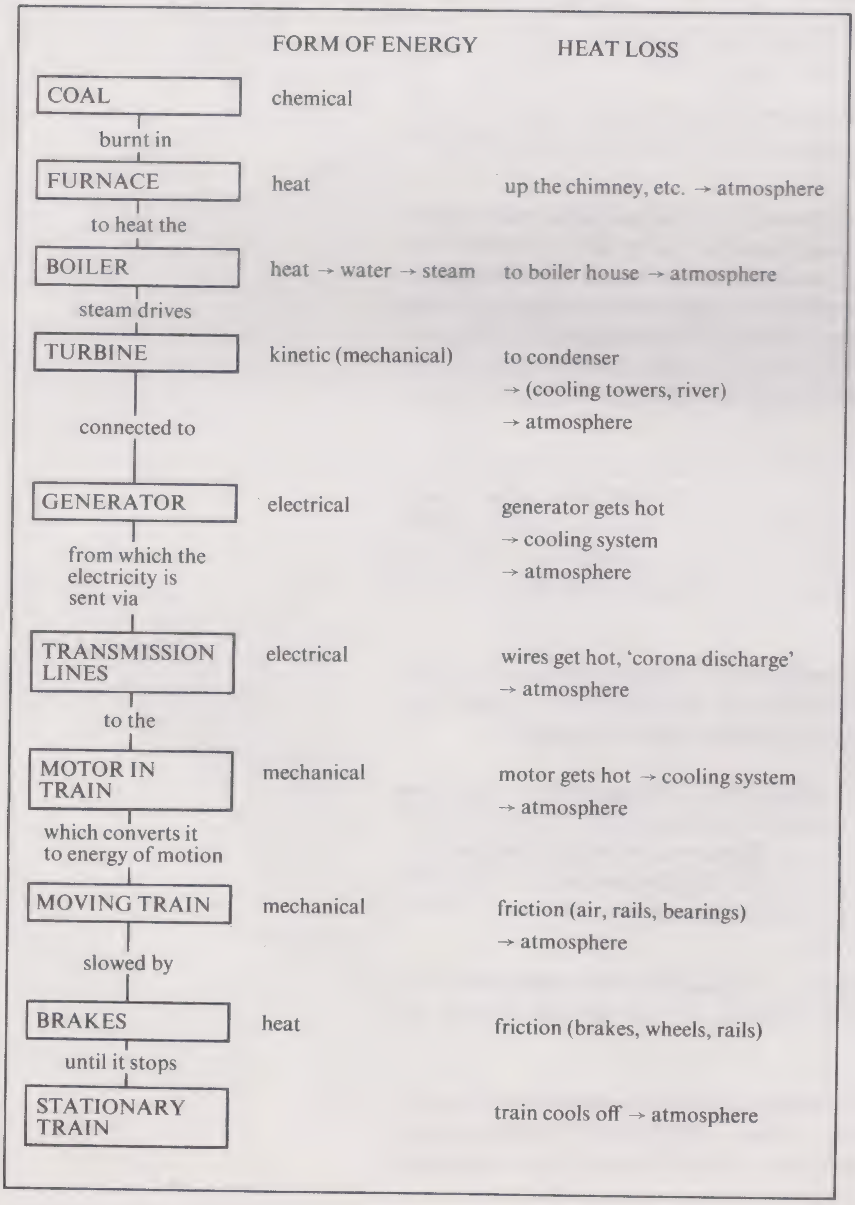


FIGURE 40 The energy conversions and transfers from a power station to an electric train.

as chemical energy (stored in the coal) is converted over a very short period into heat, which ends up in the atmosphere or maybe in a river or in the sea. In the example shown in Figure 40, all of the stored energy is rapidly converted to heat but, in other situations, some of the energy from the fuel can be stored for long periods in other forms. When an electric crane is used in the construction of a building, then the gravitational energy may be stored for centuries, and it is only when the building collapses or is demolished that the stored energy eventually ends up as heat energy.

But why, you may ask, is the energy *lost* when it is converted from one form to another? Would it not be possible to collect up the heat energy that has been lost to the surroundings from the buildings of a big city and somehow convert it back into some other, useful forms of energy that could then be used again to generate electricity or heat houses or drive cars?

Well, in fact, it *is* possible to do something of this sort. You can heat a house by using a device called a *heat-pump* to transfer heat energy from the surroundings to the house, even though the temperature outside the house is *lower* than the temperature inside it. In this process, you would make the outside a little cooler. This is no different in principle from the heat-pump in a refrigerator, which transfers heat energy from its interior (making it cooler) to the atmosphere outside, which gets hotter.

But—and this is the big snag—to make a device like this work *you have to supply it with energy*. (Your fridge will not work if you unplug it from the mains!) The result of this is that, however clever you are in designing your energy recovery system, you will only be able to recover some of this energy, because the rest is needed to make the system work.

This is an example of a very important general law of nature which says that it is *impossible* in principle to convert any amount of heat energy completely into any other form of energy. The branch of science of which this law is an important part is called *thermodynamics*: this subject, as its name suggests, has to do with heat and motion, but we shall not need to go further into it in this Course.

thermodynamics

Since it is a fundamental thermodynamical principle that prevents us from 'recycling energy', the problem of having sufficient supplies of energy is really one of having sufficient supplies of *fuel*, that is, of having enough stored energy in various convenient forms like petrol, electricity or gas. The so-called 'energy crisis' is thus, in fact, a fuel crisis. The fact that the energy from the fuels cannot be destroyed is of little importance—what matters is that the process of conversion of stored energy in fuels to heat energy in the environment is not reversible.

fuel crisis

As you will see, when we return to this topic in Unit 32, the supply of 'fossil fuels' (coal, oil, gas) is not unlimited, and alternative 'nuclear fuels' present problems of their own. Furthermore, all the stored energy in fuels ends up as heat energy in the environment, no matter what type of fuel is used. This means that there must ultimately be a limit to the rate at which fuels can be converted into heat if we are not to warm the planet up so much that we inadvertently precipitate severe and possibly disastrous climatic changes. We shall explain more about this in Unit 32.

You should now be able to explain why the so-called 'energy crisis' is actually a fuel crisis. To check that you have achieved this, the last Objective of the Unit, try SAQ 24.

SAQ 24 State briefly why the 'energy crisis' is actually a fuel crisis.

Appendix 1 Results of the experiment with the colliding objects

(a) *Conservation of energy*

We measured the distance travelled by B in 0.5 s after the collision to be $(1.10 \pm .05) \times 4.8 \times 10^{-2}$ m. Hence:

$$v_B = (1.06 \pm 0.05) \times 10^{-1}\,\mathrm{m\,s^{-1}} \quad \text{and}$$

$$v_B^2 = (1.12 \pm .11) \times 10^{-2}\,\mathrm{m^2\,s^{-2}}$$

Since

$$v_A^2 = (5.11 \pm 0.23) \times 10^{-2}\,\mathrm{m^2\,s^{-2}},$$

$$v_A^2 + v_B^2 = (6.23 \pm 0.25) \times 10^{-2}\,\mathrm{m^2\,s^{-2}}$$

which is equal to $u_A^2 + u_B^2$, within the limits of experimental error. Hence, equation 10 is satisfied and kinetic energy is conserved in the collision.

(b) *Conservation of momentum*

In order to verify that momentum is conserved in the collision, we must show that:

$$u_A + u_B = v_A + v_B \qquad (12)$$

where u_A, u_B, v_A and v_B now denote velocities, not speeds. The difference between the meanings of these terms is crucial—'velocity' means the rate at which an object is moving *in a given direction*, whereas the term 'speed' refers only to the object's rate of movement.

The convention that we shall use here is that when an object is moving to the right, its velocity is positive, and that when it is moving to the left, its velocity is negative. If we change the meaning of u_A to be the velocity (rather than the speed) of A before the collision and do the same for u_B, v_A and v_B, then

$$u_A = +(1.10 \pm 0.05) \times 10^{-1}\,\mathrm{m\,s^{-1}}$$

$$u_B = -(2.30 \pm 0.05) \times 10^{-1}\,\mathrm{m\,s^{-1}}$$

$$v_A = -(2.26 \pm 0.05) \times 10^{-1}\,\mathrm{m\,s^{-1}}$$

$$v_B = +(1.06 \pm 0.05) \times 10^{-1}\,\mathrm{m\,s^{-1}}$$

Hence,

$$u_A + u_B = (-1.20 \pm 0.07) \times 10^{-1}\,\mathrm{m\,s^{-1}}$$

$$v_A + v_B = (-1.20 \pm 0.07) \times 10^{-1}\,\mathrm{m\,s^{-1}}$$

The total momentum of A and B before the collision is equal to their total momentum afterwards, within the limits of experimental error. The principle of conservation of momentum is therefore confirmed.

Aims and Objectives

Aims

The main Aims of this Unit are:

(a) To describe the energy conversions that take place in simple processes and to stress that, in *every* conversion, energy is conserved. (Objectives 1, 2 and 21)

(b) To quantify kinetic energy, gravitational energy, heat energy and electrical energy. (Objectives 3–13 and 19)

Two other aims of the Unit are:

(c) To describe and apply a simple model of the structure of matter and to show how this helps us to understand the concepts of heat and temperature. (Objectives 14–16)

(d) To state and discuss the law which describes the interaction between stationary, point-like charged particles and to define the concept of electric current. (Objectives 17, 18 and 20)

Objectives

After you have studied this Unit you should be able to:

1 Describe the various energy inputs and energy conversions that are part of everyday life. Recognize the importance of energy in a wide variety of scientific phenomena. (SAQs 1–3)

2 Make use of the fact that energy can be transferred or converted from one form into another, to justify that the following have energy: a moving object, a body raised in a gravitational field, a stretched or compressed spring, a hot object, chemicals, electric currents, light, sound and matter. (SAQs 1–3)

3 Relate the energy E transferred to an object by a constant force to the force F exerted on the object and the distance d that it moves ($E = F \times d$). (SAQs 4 and 17)

4 State the principle of conservation of energy and apply it to a variety of energy conversions. (SAQ 4, 11–13, 16 and 17)

5 Recognize that there are different units of energy, be able to convert from one set of units to another and use a consistent set of units when calculating energy. (SAQ 5, 10–12)

6 Recall that power is the rate of conversion of energy and be able to solve simple problems involving this relationship. (SAQ 6)

7 Relate the energy transferred to an object by a varying force to the area under the graph of the force plotted against the distance travelled by the object. For simple cases, use the graph to evaluate the energy transferred (SAQ 7)

8 Recall that $E_k = \frac{1}{2}mv^2$ and—given any two of the quantities E_k, m and v—calculate the third. (SAQs 8 and 13)

9 Recall that E_k is conserved in elastic collisions and apply the fact to two-body collisions with one unknown E_k. Also, recall that the total momentum is conserved in *any* collision. (SAQ 9)

10 Recall that the gravitational energy E_g of an object, of mass m, with respect to the floor is mgh where h is its height above floor. Be able to apply this to simple situations. (SAQs 11–13)

11 Sketch and interpret graphs that show the variation of E_k, E_g and total energy of a falling object. (SAQ 14)

12 Recall that the heat energy transferred to an object is equal to the product of its mass, its specific heat and its increase in temperature. (SAQs 15–17)

13 Be able to do simple calculations to determine the amount of heat energy required to heat a substance from one temperature to another. (SAQs 15 and 17)

14 Recall that the average kinetic energy of the atoms in a substance increases as its temperature is increased. (SAQ 18)

15 Recall the approximate form of the Maxwell–Boltzmann distribution of the speeds (or the kinetic energies) of the atoms in a gas. (SAQ 18)

16 Relate qualitatively the three states of matter to the dependence of the average kinetic energy of the constituent atoms on temperature. (SAQ 19)

17 Recall that there is both positive and negative charge, that the electrostatic force between stationary, point-like charged objects is attractive if they have charges of opposite sign, repulsive if they have charges of the same sign, and that there is no force between them if one or both of them is uncharged. (SAQ 20)

18 Recall Coulomb's law, which states that the electrostatic force between two point-like, stationary objects is directly proportional to the product of the charges on them and is *inversely* proportional to the square of the distance between them. (SAQ 20)

19 Recall that the electrical energy $E_{el} = QV$, and be able to do simple calculations involving the conversion of this energy into other forms of energy. (SAQs 21 and 23)

20 Recall that the electric current I is defined as the rate of flow of charge. (SAQs 22 and 23)

21 Be able to explain in simple terms why the 'energy crisis' is actually a fuel crisis. (SAQ 24)

ITQ answers and comments

ITQ 1 From equation 3, the energy transferred to the table is $50\,\text{N} \times 10\,\text{m} = 5 \times 10^2\,\text{N m} = 5 \times 10^2\,\text{J}$.

ITQ 2 1 kilowatt $= 1 \times 10^3$ watts $= 1 \times 10^3\,\text{J s}^{-1}$. Therefore, 1 kilowatt-hour $= (1 \times 10^3\,\text{J s}^{-1}) \times (3.6 \times 10^3\,\text{s})$, since 1 hour $= 3.6 \times 10^3\,\text{s}$. Hence 1 kilowatt-hour $= 3.6 \times 10^6\,\text{J}$.

ITQ 3 The right-hand side of equation 8 is $\frac{1}{2}mv^2$. The dimensions of this are the dimensions of mass m multiplied by the square of the dimensions of speed. Thus, the dimensions of $\frac{1}{2}mv^2$ are [mass] $\times$ ([length]/[time])^2, which are the dimensions of energy, as we showed in sub-Section 4.2.

ITQ 4 In each position of the ball shown in Figure 24, the total energy of the ball is *constant*: $E_g + E_k + E_{st} = mgh$. Thus, the energy of the ball is conserved.

ITQ 5 From equation 21, the energy that must be transferred to the electron is $1.6 \times 10^{-19}\,\text{C} \times 1\,\text{V} = 1.6 \times 10^{-19}\,\text{J}$, which is otherwise known as 1 electronvolt (see Table 3).

ITQ 6 The energy E_{el} transferred to the device is given by equation 21, $E_{el} = QV$, where Q is the charge that flows through the connecting wires in time t. Equations 22 says that the current I which flows is given by Q/t. Hence, putting this result in equation 21, we find $E_{el} = VIt$.

The power-rating P of the device is defined as the rate at which it converts energy (equation 4).

Hence $P = E_{el}/t = VI$.

In words, the power-rating of an electrical device is the product of the current that flows through it and the voltage of its electricity supply.

SAQ answers and comments

SAQ 1 When the gymnast is descending through the air, as shown in Figure 2a, she is above the ground and so has gravitational energy. She is also moving and so has energy of motion—kinetic energy. When she hits the trampoline she is prevented from falling any further and is stopped moving (Figure 2b). She is still above the ground so that she still has gravitational energy, although not as much as in Figure 2a. Her kinetic energy is transformed into the strain energy stored by the trampoline. This strain energy is then converted back to kinetic energy and she is propelled upwards until momentarily she stops moving (has no kinetic energy) and has only gravitational energy (Figure 2c).

SAQ 2 The child transfers some muscular energy to the catapult's elastic which acquires strain energy. When the stone is released, this strain energy is converted into energy of motion, kinetic energy, of the stone. Since the stone is always above the ground it always has gravitational energy.

When the stone strikes the pane of glass it stops moving and it transfers its kinetic energy to the strain energy of the glass. The glass then shatters as this form of energy is converted into kinetic energy of the fragments of glass that fly all over the place. Since you would hear the glass shatter, some of the stone's energy must have been converted to sound energy.

SAQ 3 The electric fire converts most of its supply of electrical energy to heat energy. But since the bars of the fire glow, some of the energy supply must be converted to light energy.

SAQ 4 The net constant force on the car is 200 N and moves the car 0.5 km = 500 m. So the energy transferred into the car is 500 m × 200 N = 10^5 J. This energy is converted to heat energy of the road and of the car's bearings and tyres, because of friction.

SAQ 5 (a) From Table 3, 1 kilowatt-hour = 3.6×10^6 J. So, if electrical energy costs 3p per kilowatt-hour, it costs $3/(3.6 \times 10^6)$p per joule, that is 8.3×10^{-7}p per joule.

(b) The cost of running the light bulb for an hour

$$= 8.3 \times 10^{-7} \times 3.6 \times 10^5\text{p}$$
$$= 0.3\text{p}$$

The cost of heating the bath-water

$$= 8.3 \times 10^{-7} \times 2 \times 10^7\text{p}$$
$$= 16.6\text{p}$$

It is more than fifty times less expensive to run the light bulb for an hour than it is to heat the bathwater. The conclusion to be drawn from this is that if you want to save money on your fuel bills, it is much more important to take care not to heat more water for your bath than you need, than it is to worry about the odd light's being left on for a few minutes. It costs far more to heat a home than it does to keep it well lit.

SAQ 6 The total amount of energy coming from the energy supply in five minutes is $(1\,000\,\text{J s}^{-1}) \times (5 \times 60\,\text{s}) = 3 \times 10^5$ J. Since 99 per cent of this energy is converted into heat energy, the total amount of electrical energy converted into heat in five minutes is $(99/100) \times 3 \times 10^5\,\text{J} = 2.97 \times 10^5$ J.

SAQ 7 The energy transferred to the object is equal to the area under the graph. This area can be split into two parts (see Figure 41).

The area of a triangle is the half of the product of its base and its height. (If you did not know this, you should refer to MAFS, Block 4.) So the area of triangle ABC = $\frac{1}{2} \times (3m) \times (10\,\text{N}) = 15$ J. The area of triangle CDE = $\frac{1}{2} \times (2\,\text{m}) \times (4\,\text{N}) = 4$ J. So the total area shaded, that is the total amount of energy transferred to the object is 15 J + 4 J = 19 J. MAFS 4

The action of the force may be described as follows: a force of 10 N is applied to the object and this force uniformly decreases in magnitude until the object has travelled 3 m at which point no force acts on it. After that, the force on the object increases until it has travelled another 2 m when the force is no longer applied.

SAQ 8 The athelete is of mass $m = 50$ kg and is moving with speed $v = 10\,\text{m s}^{-1}$. So the athlete's kinetic energy:

$$= \tfrac{1}{2}mv^2 = \tfrac{1}{2} \times 50\,\text{kg} \times (10\,\text{m s}^{-1})^2$$
$$= 2.5 \times 10^3\,\text{m}^2\,\text{s}^{-2}\,\text{kg}$$
$$= 2.5 \times 10^3\,\text{J}$$

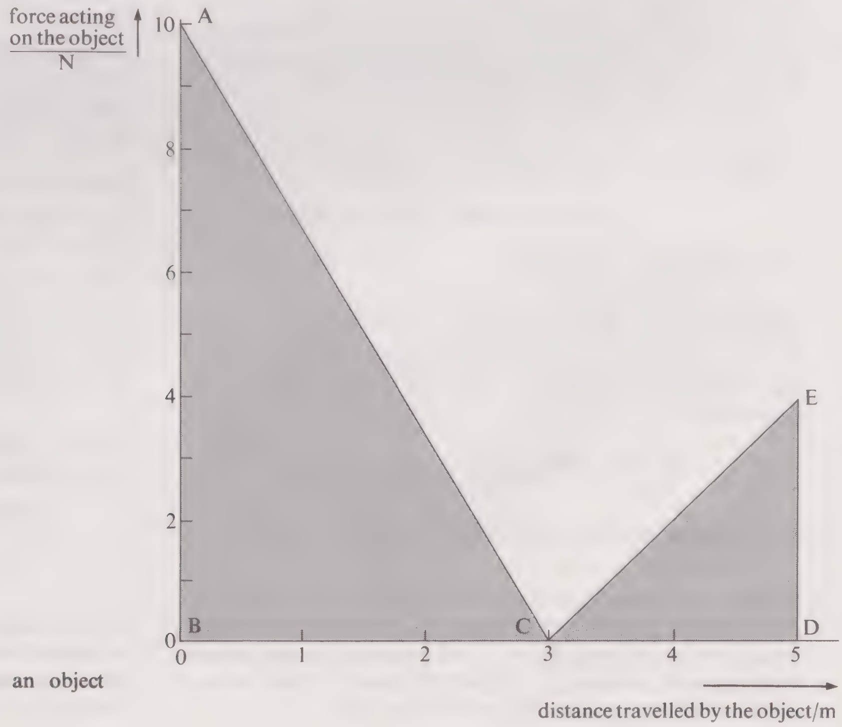


FIGURE 41 Graph of the force acting on an object plotted against the distance that it travels.

Suppose that the bullet is moving with speed u. Its kinetic energy would be $\frac{1}{2} \times (2 \times 10^{-3}\,\text{kg}) \times u^2 = 10^{-3}u^2\,\text{kg}$. If the bullet's kinetic energy is *equal* to that of the athlete,

then $\quad 10^{-3}u^2\,\text{kg} = 2.5 \times 10^3\,\text{kg}\,\text{m}^2\,\text{s}^{-2}$

Therefore $\quad u^2 = 2.5 \times 10^6\,\text{m}^2\,\text{s}^{-2}$

$$u = 1.6 \times 10^3\,\text{m}\,\text{s}^{-1}$$

So, for the bullet to have as much kinetic energy as the athlete, it would have to be moving at $1.6 \times 10^3\,\text{m}\,\text{s}^{-1}$.

SAQ 9 Let the mass of object X = m kg. Then the mass of object Y = $2m$ kg.

The kinetic energy of X before the collision $= \frac{1}{2} \times m \times (8)^2\,\text{J} = 32m\,\text{J}$

The kinetic energy of Y before the collision $= \frac{1}{2} \times 2m \times (2)^2\,\text{J} = 4m\,\text{J}$

The kinetic energy of X after the collision $= \frac{1}{2} \times m \times \left(\frac{16}{3}\right)^2\,\text{J} = \frac{128m}{9}\,\text{J}$

Since the collision is elastic, the total kinetic energy E_k of X and Y is the same before the collision as it is afterwards:

total E_k of X and Y before the collision = total E_k of X and Y after the collision

$$32m\,\text{J} + 4m\,\text{J} = \frac{128m}{9}\,\text{J} + E_k \text{ of Y after the collision}$$

So the total E_k of Y after the collision is:

$$32m\,\text{J} + 4m\,\text{J} - \frac{128m}{9}\,\text{J} = \frac{196m}{9}\,\text{J}$$

Let the speed of Y after the collision be v_Y, then the kinetic energy of Y after the collision is:

$$\tfrac{1}{2} \times (2m) \times (v_Y)^2 = mv_Y^2$$

Hence, $\quad mv_Y^2 = \frac{196m}{9}$ and $v_Y = \frac{14}{3}\,\text{m}\,\text{s}^{-1}$

The other quantity that is conserved in the collision is the total *momentum* of X and Y. To see that this is, in fact, the case, we need to write down the *velocities* of X and Y before and after the collision. The difference between the velocity and speed is that the former includes the direction of motion of the object. Before the collision, X is travelling towards the left whereas Y is travelling in the opposite direction—we say that the velocity of X is $+8\,\text{m}\,\text{s}^{-1}$ and that the velocity of Y is $-2\,\text{m}\,\text{s}^{-1}$.

Similarly, the velocity of X after the collision is $-(16/3)\,\text{m}\,\text{s}^{-1}$ and that the velocity of Y after collision is $+(14/3)\,\text{m}\,\text{s}^{-1}$.

	before the collision	*after the collision*
Momentum of X:	$m \times 8\,\text{kg}\,\text{m}\,\text{s}^{-1}$	$m \times (-\frac{16}{3})\text{kg}\,\text{m}\,\text{s}^{-1}$
Momentum of Y:	$2m \times (-2)\,\text{kg}\,\text{m}\,\text{s}^{-1}$	$2m \times \frac{14}{3}\,\text{kg}\,\text{m}\,\text{s}^{-1}$

The total momentum of X and Y *before* the collision is, therefore, $(8m - 4m)\,\text{kg}\,\text{m}\,\text{s}^{-1} = 4\,\text{kg}\,\text{m}\,\text{s}^{-1}$. *After* the collision, their total momentum is:

$$\left(\frac{-16m}{3} + \frac{28m}{3}\right)\text{kg}\,\text{m}\,\text{s}^{-1} = 4\,\text{kg}\,\text{m}\,\text{s}^{-1}$$

As you can see, the total momentum is conserved.

SAQ 10 The dimensions of mgh are given by the product of the dimensions of m, g and h. The dimensions of m are by definition [mass], that of g is [length][time]$^{-2}$ and that of h is [length]. Hence the dimensions of mgh are [mass][length]^2[time]$^{-2}$. These are the dimensions of energy (derived in sub-Section 4.2).

SAQ 11 By the principle of conservation of energy:

muscular energy transferred

$= $ gravitational energy gained by the bag of potatoes

$= (3\,\text{kg}) \times (9.8\,\text{m}\,\text{s}^{-2}) \times (3.5 \times 0.31\,\text{m})$

$= 31.9\,\text{kg}\,\text{m}^2\,\text{s}^{-2} = 31.9\,\text{J}$

SAQ 12 The slimmer's mass is 63.6 kg. If her muscular energy is converted into gravitational energy, the amount of muscular energy that is required to climb the stairs once is:

gravitational energy of the slimmer at top of the Tower with respect to the bottom $= (63.6\,\text{kg}) \times (9.8\,\text{m}\,\text{s}^{-1}) \times (170\,\text{m})$

$= 1.1 \times 10^5\,\text{J}$

From Table 3, 1 Calorie $= 4.2 \times 10^3$ J. Hence, in walking up the Tower once, she 'walks off':

$$\frac{1.1 \times 10^5\,\text{J}}{4.2 \times 10^3\,\text{J}\,(\text{Calorie})^{-1}} = 26.2 \text{ Calories},$$

only 13 percent of the number she 'consumed' in eating the strawberries and cream. It takes a lot of exercise to work off only a few Calories!

The second assumption is not really correct. If you have ever quickly climbed a large number of stairs, you will know that you get hot—some of the slimmer's muscular energy would be converted into heat energy as well as into gravitational energy.

SAQ 13 When the suitcase is 20 m above the ground, its gravitational energy with respect to the ground is equal to $mg \times 20$, where m is its mass and where g is the acceleration due to gravity. When the suitcase hits the ground, this energy will have been completely converted to kinetic energy, so, by the principle of conservation of energy:

$$mg \times 20 = \tfrac{1}{2}mv^2$$

So that $\quad v^2 = 40g = 40 \times 9.8\,\text{m}^2\,\text{s}^{-2}$

$$v = 19.8\,\text{m}\,\text{s}^{-1}$$

The suitcase will be moving at $19.8\,\text{m}\,\text{s}^{-1}$ when it hits the floor. If the man had walked up a few more stairs before he threw it off, he would have transferred some more muscular energy to the suitcase, which would, in turn, have acquired more gravitational energy. It would, therefore, have more energy of this form to convert to kinetic energy, and so it would be moving more quickly when it hits the floor.

The piece of paper would probably float slowly to the floor and arrive there much later than the suitcase, which would fall straight down. You saw in the text that the speed of an object when it hits the floor should be the same regardless of the object's mass provided *only* the gravitational force acts on it (see equation 14). The reason why the paper falls so slowly is that it is physically large for its small weight and so is sensitive to air resistance and to the currents of air circulating in the atmosphere around it.

If the piece of paper and the suitcase had been dropped in a vacuum (in which there is no air to circulate and to provide resistance to motion), they would both take the same time to fall and would be travelling at the same speed when they reached the ground. (There was a demonstration of this effect in TV 03.)

SAQ 14 The energy of the pebble when it is at the top of the cliff is purely gravitational:

its energy $= mgh$

$= (2 \times 10^{-3}\,\text{kg}) \times (10\,\text{m}\,\text{s}^{-2}) \times 10^2\,\text{m}$

$= 2\,\text{kg}\,\text{m}^2\,\text{s}^{-2} = 2\,\text{J}$

By the principle of conservation of energy, this is the total energy of the pebble *throughout* its fall to the ground. When it reaches the ground, its energy will be purely kinetic. The energy graph that describes the motion of the pebble is shown in Figure 42.

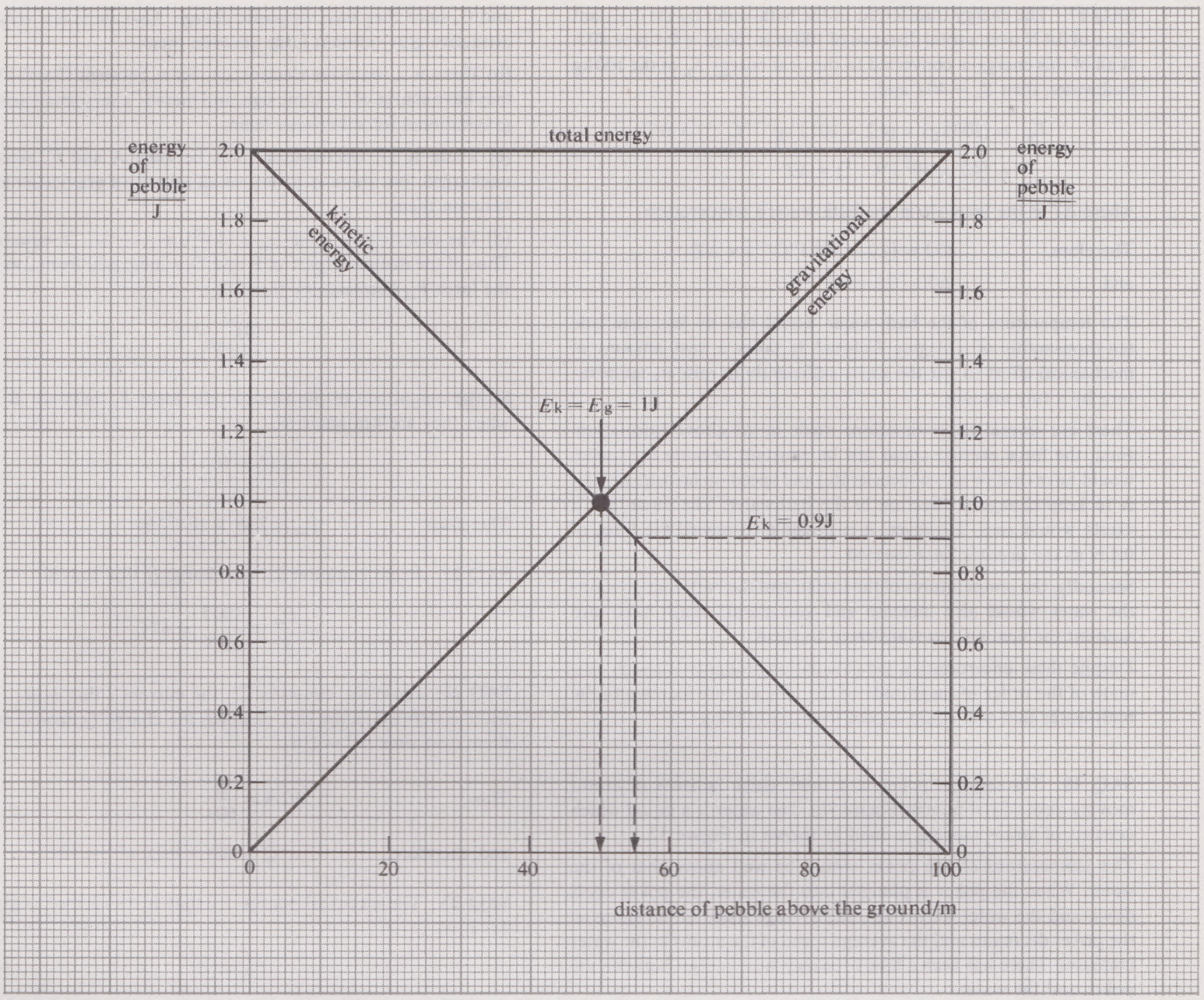


FIGURE 42 Energy graph of the pebble falling from the top of a cliff to the shore.

The gravitational energy E_g of the pebble is equal to its kinetic energy E_k when the two lines intersect. At this point, $E_k = E_g = 1\,\mathrm{J}$ and the pebble is halfway to the shore (i.e. it has travelled 50 m). When the pebble is moving with speed $u = 30\,\mathrm{m\,s^{-1}}$, its kinetic energy $E_k = \frac{1}{2} \times \text{mass} \times u^2$.

Therefore, $$E_k = \tfrac{1}{2} \times (2 \times 10^{-3}\,\mathrm{kg}) \times (30\,\mathrm{m\,s^{-1}})^2 = 0.9\,\mathrm{J}$$

From the graph, you can see that when the pebble has this kinetic energy its height above the ground is 55 m.

SAQ 15

The energy transferred to the liquid

= mass of the liquid × its specific heat × its temperature change

in *both* cases.

Thus, for the water, which has specific heat $4.2 \times 10^3\,\mathrm{J\,kg^{-1}\,{}^\circ C^{-1}}$:

$$20\,\mathrm{J} = (0.1\,\mathrm{kg}) \times (4.2 \times 10^3\,\mathrm{J\,kg^{-1}\,{}^\circ C^{-1}}) \times \Delta T_w$$

where ΔT_w is the increase in the temperature of the water.

Therefore, $$\Delta T_w = 4.8 \times 10^{-2}\,{}^\circ\mathrm{C}.$$

For the paraffin, which has specific heat $2.1 \times 10^3\,\mathrm{J\,kg^{-1}\,{}^\circ C^{-1}}$

$$20\,\mathrm{J} = (0.1\,\mathrm{kg}) \times (2.1 \times 10^3\,\mathrm{J\,kg^{-1}\,{}^\circ C^{-1}}) \times \Delta T_p$$
$$\Delta T_p = 9.5 \times 10^{-2}\,{}^\circ\mathrm{C}$$

where ΔT_p is the increase in the temperature of the paraffin. The temperature rise of the paraffin is greater than that of the water by:

$$\Delta T_p - \Delta T_w = 4.7 \times 10^{-2}\,{}^\circ\mathrm{C}$$

Notice the smallness of the increases in the temperatures of the two liquids—they are between one-tenth and one-hundredth of a degree Celsius (centigrade). Such increases are very hard to measure and this is why Joule's experiment is a very hard one to do successfully. Joule, himself an outstanding experimental physicist, spent about seven years refining the design of his apparatus so that he could measure accurately the heat energy transferred mechanically to liquids.

SAQ 16 You wish to know how much energy is required to raise the temperature of the milk from room temperature to the temperature at which it boils. You would, therefore, need to know the temperature of the milk before you turned the heat on T_{in}, and its boiling temperature T_B. Also, you would need to know the mass m of the milk, and its specific heat c_m. Then the energy required to raise its temperature by $(T_B - T_{in})$ is $m \times c_m \times (T_B - T_{in})$.

Also you would have to find out how much heat energy is required to heat the saucepan from room temperature to the temperature at which milk boils. You would need these two temperatures, the mass of the saucepan and its specific heat.

Finally, you would need to take into account the energy 'lost' to the surrounding atmosphere. To find the total amount of energy required, you would need to use the principle of conservation of energy:

energy supplied = energy required to raise the temperature of the milk and saucepan + energy 'lost' to surroundings

SAQ 17 The energy transferred to the bath-water by the constant force of 0.4 N over a total distance of 100 m is 100 m × 0.4 N = 40 J. If all of this energy is converted to the heat energy E_h of the 100 kg bathwater, then $E_h = 40$ J and:

$$E_h = (100\,\text{kg}) \times (4.2 \times 10^3\,\text{J kg}^{-1}\,°\text{C}^{-1}) \times \Delta T$$

$$= (4.2 \times 10^5\,\text{J}\,°\text{C}^{-1}) \times \Delta T$$

where ΔT is the increase in the bath-water's temperature.

Therefore, $40\,\text{J} = (4.2 \times 10^5\,\text{J}\,°\text{C}^{-1}) \times \Delta T$

and $\Delta T = 9.5 \times 10^{-5}\,°\text{C}$

The temperature of the bath-water would rise by less than one ten-thousandth of a degree Celsius! It takes a vast amount of mechanical effort to stir the water sufficiently to raise its temperature by a tiny amount.

There are several approximations made in the above calculation. First, the force exerted could not be constant because the loofah would have to slow down (decelerate) and speed up (accelerate) if it is to keep changing direction in the bathwater. The force that it exerts would *vary*. However, it is possible to regard the force of 0.4 N as the *average* force exerted.

Secondly, the temperatures of the loofah and the bath that contains the water would also increase and you should really take into account the heat energy transferred to them.

Despite these uncertainties, the calculation still gives a rough estimate of the order of magnitude of the temperature increase of the bath-water that you could expect from the stirring.

SAQ 18 The red-hot poker is a solid which consists of atoms moving-about fixed points (Figure 36). The water is a liquid which consists of atoms moving around as shown in Figure 37.

The temperature of the poker would be well above that of the water. When the poker is plunged into the water, the poker cools down and the water warms up—the average speed of the atoms in the poker decreases and the average speed of the atoms in the water increases. There has been a flow of energy, heat energy, between the poker and the water.

Some steam will be given off after some energy has been transferred to the poker, as some of the atoms of water acquire enough energy to escape from the forces that hold them together in the liquid. The distribution of the speeds of the atoms in the steam will be a Maxwell–Boltzmann distribution. Your sketch of this should resemble Figure 34.

SAQ 19 Statement (a) is true. Statement (b) is false—the forces between the atoms do not change when a substance changes its state, but the average kinetic energy of its constituents does change. Statement (c) is also false, because it is the *average* kinetic energy of the atoms in the gas that increases with the temperature of the gas.

SAQ 20 (a) There is an attractive electrostatic force between B and C, since they have opposite charge. Also, there is a very small attractive gravitational force between them.

(b) There is a repulsive electrostatic force between C and D, since they have charge of the same sign, and there is a very small attractive gravitational force between them.

(c) There is no electrostatic force between A and C, since A is uncharged, but there is a very small attractive gravitational force between them.

(d) The electrostatic force $F_{el} \propto (1/r^2)$, as you saw in equation 19. Thus, if the distance apart of B and D is increased from 2 m to 4 m the force F_{el} decreases by the ratio:

$$\frac{(2)^2}{(4)^2} = \frac{1}{4}$$

So the magnitude of the electrostatic force F_{el} between B and D when they are 4 m apart is:

$$\frac{1.15 \times 10^{-28}}{4}\,\text{N}$$

Therefore $F_{el} = 2.88 \times 10^{-29}\,\text{N}$

SAQ 21 From equation 21, the charge Q that flowed:

$$= \frac{E_{el}}{V} = \frac{100\,\text{J}}{1.5\,\text{V}} = 67\,\text{C}$$

SAQ 22 From the equation 22, the current I that flowed in the wires is defined as the rate at which the charge Q flowed through them over time t, $I = Q/t$

Thus, $0.2\,\text{A} = \dfrac{Q}{60\,\text{s}}$

and, therefore, $Q = 60\,\text{s} \times 0.2\,\text{C s}^{-1} = 12\,\text{C}$

SAQ 23 The electrical energy E_{el} that is transferred is given by equation 21:

$$E_{el} = QV$$

where Q is the charge that flows in the wires and where V is the voltage of the supply. Since 40 A flow for 5 s, the total amount of charge Q that flowed through the wires is (from equation 22):

$$Q = 40\,\text{A} \times 5\,\text{s} = 2 \times 10^2\,\text{C}$$

Hence, $E_{el} = 2 \times 10^2\,\text{C} \times 12\,\text{V} = 2.4 \times 10^3\,\text{J}.$

SAQ 24 The main point that you should have made is that there is a fundamental thermodynamical principle which says that it is not possible to convert completely a supply of heat energy into other forms of energy. This means that we cannot recycle all of the heat energy converted from other forms.

The problem is not that we are short of supplies of energy—rather, it is that we are short of supplies of *fuel*, that is of energy stored in convenient forms like coal, petrol and gas.

0 335 08058 8
The Open University Press